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DoD Investment Strategy for Vacuum Electronics R&D and Investment Balance for RF Power Vacuum Electronics and Solid State R&D

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A TRI-Service Investment Strategy and Balance is described for the DoD's needs for RF Power Electronic Components.

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DoD INVESTMENT STRATEGY FOR VACUUM ELECTRONICS R&D

AND

INVESTMENT BALANCE FOR RF POWER VACUUM ELECTRONICS AND SOLID-STATE R&D

REPORT

BY THE

AD HOC TRI-SERVICE COMMITTEE

July 20, 2001

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1. EXECUTIVE SUMMARY

Microwave and millimeter-wave power amplifiers are essential front-end building blocks for most DoD electronic systems including radar, electronic warfare, communication and smart weapons. The ability to provide sufficient power output, over a sufficiently broad bandwidth with maximum power added efficiency and high gain is of paramount importance for many current systems. Most future military electromagnetic systems, in contrast to commercial systems, will require even higher power over a broader bandwidth, as well as high linearity, phase stability, and very high reliability; some systems will require amplifiers that possess all of these characteristics simultaneously. These attributes are the ones that collectively provide our fighting forces with an electro-magnetic (E/M) advantage over their adversaries; they are typically not available from so-called commercial-off-the-shelf (COTS) amplifiers. Microwave and millimeter-wave amplifiers can be grouped into two broad categories, solid-state (SS) and vacuum electronics (VE). Each type has its advantages and drawbacks and each lends itself for use in different and changing system applications of importance to the DoD.

In spite of the clear importance of continuing to maintain a competitive edge in microwave and millimeter wave power amplifier technology, for a number of years, DoD S&T investment in microwave and millimeter-wave power amplifier technology has been declining. Figs. 1.2a and 1.2b show the recent-year funding trends for RF solid-state power amplifier, material and device technologies and RF vacuum electronics power amplifier technology. During the 1998 Technical Area Review and Assessment (TARA) for Electronics, the TARA Review Team voiced their concern about this situation and charged the Tri-Service Technology Panel on Electron Devices (TPED) with "Developing a balanced plan for vacuum electronics/solid-state". Upon subsequent review by the Defense Science and Technology Advisory Group (DSTAG), this charge was assigned the designation TARA Action Item #3.

It is the objective of this report to set forth a balanced Tri-Service investment strategy for RF vacuum electronics and solid-state power amplifier technologies.

Since the Navy, under the RELIANCE initiative, is the Category 3 agent for VE, Dr. Gerald M. Borsuk, Superintendent of the Electronics Science & Technology Division of the Naval Research Laboratory, was assigned principal responsibility for coordinating preparation of this strategy. Throughout the study and assessment procedure, numerous other individuals from the Army, Navy and Air Force all contributed their knowledge, expertise, guidance and counsel to the formulation of the plan which follows. Specifically, during 1999, an Ad Hoc Solid-state and Vacuum Electronics Tri-Service Committee, staffed by senior electronics S&T managers, was assembled. A series of Tri-Service meetings were held throughout FY00 and into FY01. These meetings culminated in two industry/academia/government workshops: the first addressing RF power requirements for transmitters, the second exploring VE and SS technology options for meeting those requirements. Tri-Service working panels, consisting of senior level electronics S&T managers, reporting to the Ad Hoc Solid-state and Vacuum Electronics

Tri-Service Committee, then assembled, analyzed, and correlated the data that was provided at these forums and developed the proposed investment plan.

Following the assignment of Action Item #3, two other related taskings were assigned. These also centered upon the issue of determining an appropriate Science & Technology (S&T) funding balance between VE and SS technologies. Specifically, the Chief of Naval Research (CNR) requested a balanced investment strategy between VE and SS. The House Armed Services Committee requested a review and assessment of VE S&T. It is the understanding of those charged with generating this report that the Navy and Congressional taskings, when completed, will be substantially satisfied by the conclusions of this report because of the intertwining nature of the requests and the technologies assessed.

The information, findings and recommendations contained in this report represent the collective judgment of the Army, Navy and Air Force study participants. The report provides a plan for adequate investment of DoD S&T funds with an appropriate balance between funding for needed advances in SS technology and funding for needed advances in VE technology.

HISTORY AND PRESENT STATUS OF SS AND VE S&T FUNDING

Between 1990 and 1995, the DARPA/Tri-Service Microwave and Millimeter wave Monolithic Integrated Circuits (MIMIC) program provided approximately $80-90 million/year for overall development of microwave and millimeter wave monolithic circuit technology, principally GaAs-based. During this period, great advances were made including development of a readily available supply of GaAs wafers, development of robust processes and manufacturing capabilities for microwave and millimeter-wave monolithic integrated circuits, emergence of computer aided capabilities for modeling and designing these circuits, advances in microwave and millimeter wave packaging, and the development and implementation of highly automated testing procedures, including those for cost effective on-wafer testing at frequencies up to 110 GHz. It is important to recognize that the technology achievements of the MIMIC program enabled the practical implementation of many DoD systems and have had the desirable collateral benefit of U.S. dominance of the wireless communication industry. In 1995, the MIMIC program ended and was followed by the much more modestly funded Microwave and Analog Front End Technology (MAFET) program. During the MAFET program, further advances were made in GaAs technology development, advances were achieved in indium phosphide (InP)-based MIMIC technology, in computer aided design capabilities at the module level, in power combining and in the exploration of wide bandgap semiconductor technology. During the decade of the 1990s, the large DARPA investment in the MIMIC and MAFET programs overshadowed Tri-Service R&D investment in solid-state RF power amplifier technology. However, particularly between 1990 and 1995, this did not have a deleterious impact on DoD capabilities because the overall investment was sufficient to provide the needed technology advances. However, **since 1999, DARPA has provided no funding for microwave and millimeter wave solid-state technology development and the Services have been unable to devote sufficient funding to continue the technology advancement needed for satisfying the needs of their future systems. The severe lack of funding is particularly serious because it has become increasingly clear that DoD systems will benefit greatly from the development of high power solid-state amplifiers fabricated from wide bandgap materials such as gallium nitride (GaN) and silicon carbide (SiC). Although promising, these technologies will require very significant amounts of S&T funding to be brought to a state of maturation necessary to make their use in DoD systems efficacious.** The integrated investment in solid-state technology in semiconductor materials and processes required for all solid-state devices, including optical and switching amplifiers, applies to a widely diffuse set of tasks with differing applications scattered throughout the Army, Navy, Air Force, BMDO, and DARPA. Figures 2.a and 2.b summarize the Tri-Service, DARPA, and BMDO historic and planned investment in solid-state and vacuum electronics R&D at this time.

In 1991, the Navy was assigned the responsibility, under Project Reliance Category 3, for meeting the VE S&T in-house needs of all of the Services. In addition, a five-year Tri-Service/DARPA program was initiated to meet the needs of the Services. This program provided enhanced capability to the military, reinvigorated the industrial sector, and encouraged highly qualified graduates to enter the field. The

program ended the long-term decline in DoD support for vacuum electronics R&D by increasing the investment three-fold to a level not experienced since the 1960's. Under the Tri-Service/DARPA program, managed directly by NRL through so-called Navy block funding, focused efforts were established for the development of the microwave power module, millimeter wave gyro-amplifiers, advanced techniques for device modeling and simulation, RF vacuum microelectronics, and advanced materials, cathodes, and magnetics. As a very compact, highly efficient, wide band transmitter module operating across microwave and millimeter wave frequencies, the MPM has proven pivotal in the development of advanced radar, electronic countermeasures, and communications capabilities for systems where efficiency, small size and weight are critical. The technology has been applied to numerous DoD systems. Under this program, the bandwidth potential of the gyro-TWT and the high power capabilities of the gyro-klystron for millimeter wave radar for target identification, counter-stealth, and ballistic missile defense were realized by the successful development of a 100 kw 700MHz W-band gyro-klystron. This level of performance represents a 20-fold increase in available power and can afford a 60-fold increase in imaging resolution compared to X-band radars based on the reduced operating wavelength. The microwave vacuum electronic device development process has been characterized historically by a time consuming cycle of first order design, cold test of circuits, redesign, device fabrication, and finally full up RF testing. Using the rapidly evolving capabilities of computer technology, an interactive suite of physics-based codes, two and three dimensional computational design tools were created for the full range of linear-beam vacuum devices. These codes are being successfully introduced into industry and have broken the old paradigm and created a new one-"first pass success". The results are a significant reduction in device development time and cost, improved performance, and enhanced physical insight leading to next-generation concepts. With the end of the Tri-Service/DARPA program in 1995, Navy investment in vacuum electronics has declined precipitously and **is now at a level so low that the ability to sustain the personnel and facilities essential for continuing necessary R&D in this area is imperiled.** The proposed decline in FY02 funding reflects Navy priorities in S&T and the Navy Future Naval Capabilities (FNC) requirements. **If the proposed funding level is not raised, the Navy will not be able to meet its RELIANCE commitments to the Army and the Air Force.**

Findings and Conclusions

S&T opportunities exist for VE to address key military needs in areas such as ultra-wideband EW, high data rate communications (terrestrial and space-based), high power low noise radar, and applications to size-constrained platforms such as UAVs, decoys, and pods. Vacuum electronics power amplifiers are playing and will continue to play a major role in DoD electromagnetic systems that require the advantages offered by this technology such as high power at any frequency in the microwave or millimeter wave range, high efficiency, wide bandwidth, and competitive cost. The availability of new design codes, tailored dielectrics, high current cathodes, and high coercivity magnets will enable significant advances in amplifier capabilities. The development of new device types, such as the multiple beam klystron, will address the present need to improve radar performance in the presence of clutter and jamming. The

use of Microwave Power Modules (MPM), which consist of a MMIC driver amplifier followed by a traveling wave tube output-stage amplifier and provides high power over a very wide bandwidth in a compact package is inhibited by their cost. Cost reduction and performance enhancements opportunities for the MPM and the Millimeter-wave Power Modules (MMPM) remain unexploited. The gyro-amplifier is unsurpassed for very high power at millimeter wave frequencies and is able to support a variety of high power millimeter wave radar concepts.

Just as the DARPA MIMIC and MAFET programs provided the enabling capability to field present GaAs-based E/M systems, **WBG technology has potential for enabling the next generation of E/M systems including systems such as National and Theater Ballistic Missile Defense and multifunctional systems that will provide significant reduction of radar cross-section, significantly improved battlefield versatility and performance and lower life cycle costs.** The MIMIC and MAFET programs also led to large benefits for to the U.S. commercial marketplace, enabling the cell phone and wireless industries. A WBG program could reasonably be expected to enable other commercial industries. While there are challenges to be addressed to bring WBG RF technology to production, there is significant leverage from the knowledge and infrastructure developed for Si and GaAs technology to facilitate this development. No technology maturation program yet exists for WBG technology.

Although the MIMIC and MAFET programs have been successfully completed, **manufacturing yields and costs of GaAs MMICs are not yet at levels that will permit DoD to utilize their capabilities to the fullest extent.**

Millimeter-wave frequencies represent an area of considerable importance to the Services. Additional funding is required to effect needed improvements in both VE and SS technology to meet Service needs at these frequencies. Above 25 GHz, RF solid-state devices currently are used to address lower power applications (less than 50 watts). They play a critical role in such systems as smart munitions, the Air Force's MILSTAR, and the Army's Future Combat System. There are additional opportunities to effectively use SS power amplifiers but expanded InP device and circuit development will be required to do so. Theoretical projections suggest that WBG devices should be applicable to amplifiers up to 50 GHz, although experimental work above 25 GHz is only now being initiated. VE devices (fast- and slow- wave) are suitable for meeting requirements for high power amplification at frequencies up to several hundred GHz. At frequencies above ~ 20 GHz, fast-wave devices are better matched to very high power production. Key applications for vacuum amplifiers in this domain include (high power) EW, radar, and communications. On the battlefield, millimeter wave systems generally have characteristics that are complementary to those of IR systems (i.e., IR systems can be blinded by fog and related environmental conditions whereas millimeter-wave systems typically do not provide images with as high resolution as does IR systems). Millimeter-wave components are also important for use in homing missiles.

There currently is no 6.3 advanced development budget specifically for RF power amplifier development and transition to an appropriate level of maturation for DoD system users.

Recommendations

Based on the above findings and conclusions, the Committee presents the following recommendations for the 5-year period FY02 – FY-06.

- **Restore applied research vacuum electronics funding to FY 98 levels of $12 million per year** to enable pursuit of the following opportunities:

  - Multiple beam klystrons (MBK) for high power radar, telecommunication, and missile seekers;
  - Gyro-amplifiers for space object identification, BMD range instrumentation, counter stealth, and target identification;
  - Highly linear TWTs for HDR communication and multifunction systems
  - Ultra wideband power boosters for EW;
  - Design code suites to support a cost-effective research and manufacturing infrastructure;
  - MMW TWTs for MMW radar, EW, and communications;
  - Tailored dielectric materials to realize - amplifiers featuring enhanced stability, high fidelity, and higher power; and
  - Scandate and non-thermionic cathodes to provide high-reliability, high-power MMW TWTs and emission gated amplifiers

- **Sponsor a combined Tri-Service initiative, comparable to the MIMIC and MAFET programs, at a funding level of $50 M per year for at least five years, to rapidly advance wide bandgap semiconductor device** technology to a point where it is viable, affordable, reliable, and ready for use in enabling new DoD electromagnetic systems. This will enable the pursuit of the following opportunities:

  - Development of better SiC and GaN substrates to improve MMIC performance and yield and lower initial cost.
  - Development of better thermal management techniques.
  - Establishment of a baseline amplifier manufacturing process and yield enhancement effort.
  - Establishment of a reliability test program.

  This investment will enable the mid-to-long-term (>5 years) transition of SS WBG power amplifier technology to new advanced military systems that require a combination of high power per element, high efficiency, broad bandwidth, or multi-function operation for satisfying a broad spectrum of radar including TBMD and NBMD, electronic warfare, smart munitions, and communications needs.

- **Provide additional support of $5 M per year (for 5 years) for producibility updates of GaAs MMIC technology and $5 M per year (for 5 years) for the**

development of InP power technology to meet the needs of DoD applications at frequencies up to 100 GHz. These investments will directly support the upgrade of legacy systems as well as enabling the near-term (1-5 years) technology transition of advanced solid-state power amplifiers to new RF military systems.

- **Insure that application specific 6.3 power amplifier component development is funded as has historically been the case including funding a 6.3 vacuum electronics Tri-Service application program at a level of $10M/year for five years.** This later effort would support initially MPMs and MMPMs for reliability and maturation programs followed by programs to advance MBK amplifiers and support vacuum electronics infrastructure. ***[ONR does not agree with this later recommendation, but believes that such a program should support the development of the best technology (vacuum electronics or solid-state electronics) for a given application].***

- **Ensure at least a $5M applied research program in wide bandgap semiconductors to pursue promising technology opportunities such as:**

  - Development of better ohmic contacts and better control of heteroepitaxial interfaces to improve efficiency and reduce prime power requirements on aircraft, spacecraft, and UAVs.
  - Development of P-type doping for GaN and its alloys for ultra low phase noise systems required to improve the tracking of targets in clutter and jamming and to increase the spectral utilization of communications systems.
  - Development of higher frequency devices well into the millimeter wave spectrum for applications to missile seekers and communications systems.

A summary of the above findings and recommendations is provided in Table 1.1 below. The specifics of the recommended plan are captured in a series of Roadmaps, which can be found in Appendix A.

FINDING	RECOMMENDATION
S&T opportunities exist for VE to address key military needs in areas such as ultra-wideband EW, high data rate communications (terrestrial and space-based), high power low noise radar, and applications to size-constrained platforms such as UAVs, decoys, and pods.	**Restore applied research vacuum electronics funding to FY 98 levels of $12 M per year**
WBG technology has potential for enabling the next generation of E/M systems including systems such as National and Theater Ballistic Missile Defense (NBMD &TBMD) and multifunctional systems that will provide significant reduction of radar cross-section, significantly improved battlefield versatility and performance and lower life cycle costs. WBG development opportunities exist for higher power devices, better p-type doping, higher efficiency devices and circuits including combining techniques, ohmic contacts, and interface control.	**Sponsor a combined Tri-Service initiative, comparable to the MIMIC and MAFET programs, at a funding level of $50 M per year for at least 5 years, to rapidly advance wide bandgap semiconductor device technology** to a point where it is viable, affordable, reliable, and ready for use in enabling new DoD electromagnetic systems **Maintain an applied research program at a level of $5M per year in wide bandgap semiconductors to pursue promising technology opportunities.**
Manufacturing yields and costs of GaAs MMICs are not yet at levels that will permit DoD to utilize their capabilities to the fullest extent. InP technology requires further focused development.	**Provide additional support of $5 M per year (for 5 years) for producibility updates of GaAs MMIC technology.**
Millimeter-wave frequencies represent an area of significant importance to the Services. Additional funding is required to effect needed improvements in both VE and SS technology to meet Service needs at these frequencies.	**Fund development of InP technology for millimeter wave applications at $5M per year.** **Fund VE technology for millimeter wave power applications as part of a coherent VE program.**
There currently is no 6.3 advanced development budgets for RF power amplifier development and transition to an appropriate level of maturation for DoD system use.	**Restore Service 6.3 funding lines or create new funding lines to support RF component transitions to production and fund a vacuum electronics Tri-Service application program at a level of $10M/year.**

Table 1.1. Summary of Findings and Recommendations

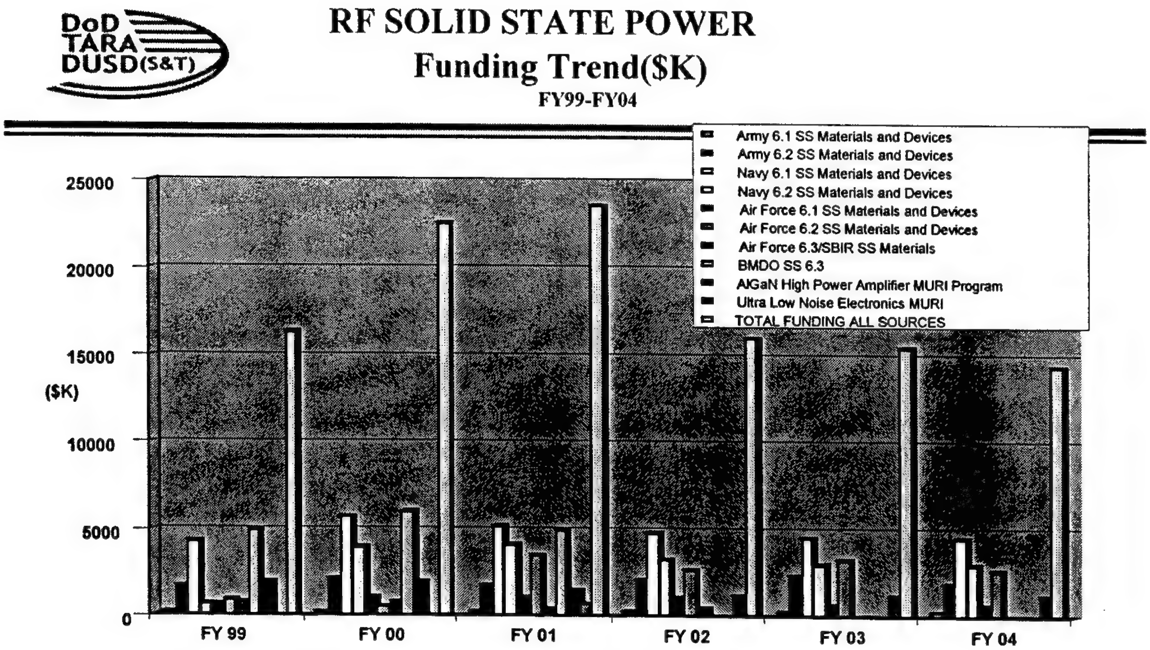

Fig. 1.2a. Tri-Service 6.1-6.3 Investment in RF Solid-state Power Amplifier, Material, and Device Technologies

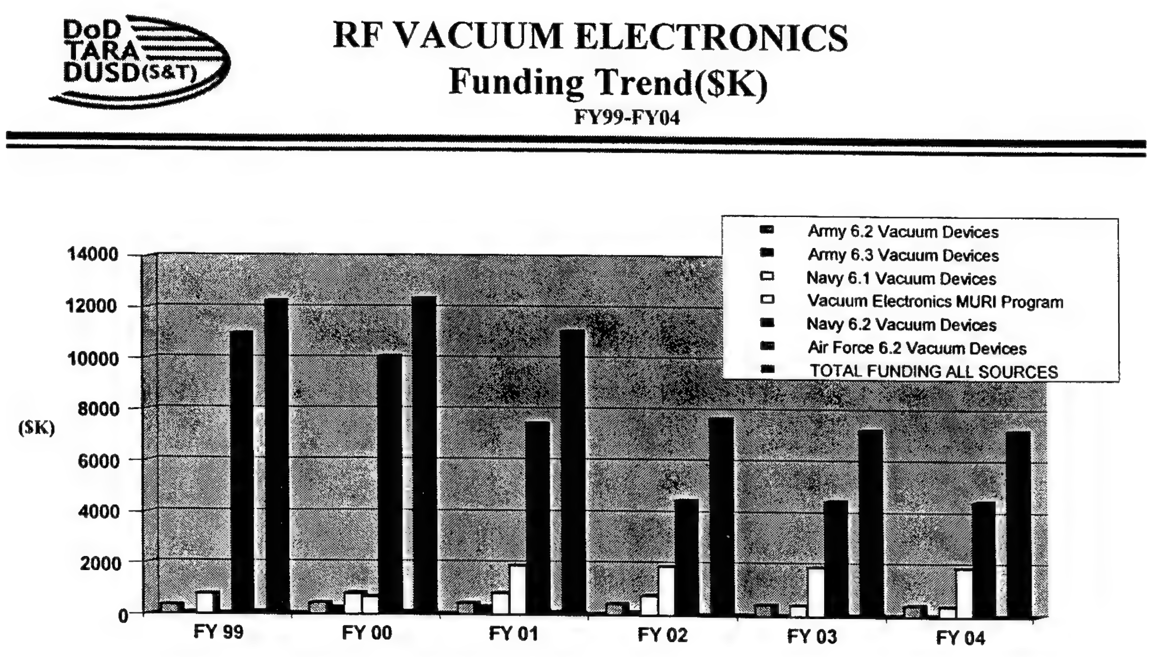

Fig. 1.2b. Tri-Service 6.1-6.3 Investment in Vacuum Electronic RF Power Amplifier Technology

2. TERMS OF REFERENCE

TARA Action Item 3 states the following: "Support must be provided to foster advances in both solid-state and vacuum electronics RF technologies to ensure the sources and components for system/subsystem designers to concurrently meet performance, cost, and packaging requirements." The recommended action is as follows: "Assess the near term and long term RF technology needs of planned DoD systems and future concepts. Prepare, for DSTAG action, a DoD investment plan for RF electronics that addresses system technology needs and ensures balance between solid-state and vacuum electronics and balance between near-term and long-term objectives. New DTOs should be identified to implement this plan."

In its report (# 106-162) on the National Defense Authorization Act for Fiscal Year 2000 (Appendix X), the House Armed Services Committee (HASC) directed the Secretary of the Navy "to assess the Department's requirements for advanced vacuum electronics technology and to report that assessment and the long-term funding plan for the Department's vacuum electronics technology program to the Congressional defense committees with the submission of the year 2001 budget request." The House Armed Services Committee expects "the Navy as the Department of Defense (DoD) executive agent for the program to insure a coordinated vacuum electronics research and development program among the military services and defense agencies, and with other federal agencies, that will meet DoD requirements for advanced vacuum electronics technology."

At the direction of Rear Admiral Paul Gaffney, Chief of Naval Research between July 1996 and June 2000, ONR 312 and NRL Code 6800 were tasked to prepare a balanced investment strategy for Navy Solid-state and Vacuum Electronics R&D.

3. INTRODUCTION AND BACKGROUND

Chapter VII of the 1999 Defense Technology Area Plan (DTAP) defines the scope and strategic goals of the Electronics program area that must be collectively satisfied to meet DoD's acquisition/warfighter needs. These constitute the foundation for RF Components technology objectives. The realization of our national objectives requires the continued superiority of our military-essential, unique RF electronics compared with that of our adversaries. The increasing scope, complexity and variety of military missions challenges our RF systems to operate with high output power that is delivered with high power added efficiency over increasingly large portions of the frequency spectrum. In addition, these systems must be flexible in terms of the operations they can perform, available as needed, and precisely suited for their intended applications. In the most stringent situations they must be capable of performing a multiplicity of functions simultaneously. The RF components sub-thrust of the DoD's Electronics S&T program, for which Vacuum Electronics and Solid-state Electronics represent the dominant implementing technologies, is poised to meet this modernization challenge through the development of new generations of highly competent electronics technology for surveillance, information dominance, and EW applications. This new, highly capable technology will, in turn, provide improved dexterity for executing national strategy and response actions.

The Army's Science and Technology Master Plan, Vol. I, Chapter IV, Technology Development, states that the Army's basic research, applied research and advanced technology development work should place a strong emphasis on technologies that could be used to upgrade currently fielded systems. It also requires emphasis on continuing assessment of long-range insights and requirements such as set forth in "future-seeing" initiatives such as the Army After Next (AAN) and the recently espoused Army Vision to guide itself into the 21st century through initiatives such as the Future Combat System (FCS). The Navy's Radar Technology Road Map describes the need for wide bandgap (WBG) semiconductor RF power devices to meet its objectives. The Navy's vision of Future Naval Capabilities also recognizes the importance of WBG semiconductor technology for meeting the requirements of the Advanced Multifunctional RF Concepts (AMRF-C) program. WBG and vacuum electronic devices are also being considered for up-grades to several EW systems (e.g. ALE-50 and IDECM). The Air Force has issued a number of high-level documents ("America's Air Force Vision," "Air Force Basic Doctrine," "Air Force Task List," and "Air Force Strategic Plan") that emphasize the need for global dominance, global reach, and global power. To meet the challenges described in these documents, it will be essential to provide our warfighters with continuous, highly accurate situational awareness, improved precision strike capabilities, and highly competent electronic warfare equipment. We derive our technology challenges, identify technical barriers that must be overcome, and propose technology solutions based upon our need to equip our warfighters with advanced capabilities such as those described above. The sensor, electronic warfare and communication systems postulated are dependent upon the success of internal and external Tri-Service RF Solid-state programs and of Category 3, Navy-led, Vacuum Electronics developments.

The House Armed Services Committee Report # 106-162 has directed the Navy to lead a DoD-wide assessment of the military requirements for advanced vacuum electronics technology and the adequacy of the planned DoD investment. The results are to be reported with the submission of the President's FY-02 Budget request. A Navy led role in this study is appropriate since the Navy is the DoD's Executive Agent for Vacuum Electronics. It has been designated as the lead Service for research and development in this topical area under Defense Reliance and its Naval Research Laboratory possesses the dominant DoD capability for research and development in that field. The Navy also supports the majority of WBG semiconductor device R&D work.

This report has bee coordinated with the OSD, and acknowledged by the other Services and Defense agencies as meeting their future needs if the proposed plan it sets forth is fully funded. It is believed that this report is fully responsive to the HASC request but it is not the Navy's official response to the HASC tasking. The Secretary of the Navy has submitted his response to the HASC direction with the President's FY02 Budget request of July, 2001.

The requirements of related studies, ordered by the Chief of Naval Research (CNR), are also included in a self-consistent manner in this TARA initiated Report. The CNR directed ONR 312 and NRL Code 6800 to evaluate and submit an investment strategy that balances the Navy's needs for RF power solid-state and vacuum electronics technologies. Since this report meets all of the collective requirements of the 1999 TARA directive, the HASC directive and the CNR's directive, it should satisfy all three of these independent but essentially identical requests.

4. NEEDED MILITARY CAPABILITIES IMPACTING RF POWER AMPLIFIER TECHNOLOGY-THE REQUIREMENTS CHALLENGE

4.1. *OPERATIONAL REQUIREMENTS*

RF electronics is the critical technology for systems operating in the microwave and millimeter wave frequency bands. The RF electronics portion of most electromagnetic systems (e.g., radar, communications, EW) typically is over 50% of overall electromagnetic system cost and, in turn, the cost of electromagnetic systems is 38 to 60 % of the overall cost of most major DoD combatant platforms. Major applications of RF technology include radar, electronic warfare, communications, and missile guidance systems. Secondary applications include range instrumentation and experimental test beds. For completeness, it is noted that a microwave directed energy weapons community also exists. Its efforts and requirements are classified and, as a result, they will not be discussed further in this report.

Practical platform constraints and increasingly demanding mission-essential requirements, coupled with promising technology advances, have created increased interest in the development of multifunction systems (i.e., systems that can perform a multiplicity of functions simultaneously using the same RF components.) These highly versatile systems are expected to provide the additional benefits of reduced personnel requirements and reduced life cycle costs. In addition, they should provide important operational advantages, including reduced radar cross-section, a significant reduction of intra-platform interference, and ideally software based reconfiguration to counter new threats.

For all types of RF systems, amplifier performance parameter goals such as peak and average power, efficiency, bandwidth, frequency range, modulation technique, phase and amplitude noise, and flexible scan switching are dictated by system architecture and specific battlefield function considerations. Conversely, RF amplifier component capabilities greatly influence system architecture. The combination and variety of required system features determine amplifier design and complexity. Platform location and other constraints also impact the choices of electronic component. **Appendix B lists the most important of DoD's currently fielded and planned RF transmitter systems. For each system type—radar, communications, electronic warfare, weapons control and multifunctional—a tabulation of the key performance parameters for the systems in that category is available.**

Energy consumption (device efficiency) limitations represent particularly difficult challenges for portable systems such as the Army man pack and for special platforms such as the Air Force's space platforms.

The primary considerations that dictate the architecture selection for military electromagnetic systems include the power-aperture product or effective radiated power requirement, platform constraints (e.g. prime power, form factor, and thermal management) and system functionality requirements (e.g. signaling characteristics, single

radiating element, sparse arrays, or dense arrays). In all cases, initial and life cycle costs are of dominant importance. The selection, for any electromagnetic system front end design, of a vacuum electronics solution, a solid-state solution, or a solution that is a hybrid of these two technologies involves conducting a complex analysis that must take into consideration all the major design elements described above. Generalities cannot be made concerning front-end design selection because of these complex design trade-offs. In the sections that follow, requirements and S&T opportunities are presented in two forms. First, they are presented in the context of ground, air, space, and sea needs. Then they are described in terms of present and envisioned needs of radar, electronic warfare and attack, communications, and multifunctional systems. In both forms, needs are presented that address the Requirements Challenges. An assessment of how well existing and envisioned capabilities of RF power amplifier technologies (S&T Opportunities) are expected to satisfy them is then presented in Chapter 5 with conclusions drawn in a way that allows formulation of a balanced and appropriate investment strategy for both vacuum electronics and solid-state technologies.

4.1.1. Ground

Most soldier man-pack electronics (communications and computers) must use as little energy as possible because of limited availability of power sources on the battlefield and weight considerations. Munitions are required to be operational after being stored for up to 20 years in hostile environments. Hence, long shelf life is essential. In addition, munitions must be capable of being activated on very short notice. Gun launched munitions must withstand up to 18,000 G's of force. Ground radar for tactical forces must be mobile in-theater (6x6 vehicle or HMMWV); delivery to the theater (C-130 compatible) requires compact size and the ability to self-repair. Ground based EW is conducted from small fixed wing and rotary winged aircraft, which have limited prime power and weight carrying capabilities. Thus, these systems also require miniaturization and the ability to operate with high efficiency. Electronics for all of these applications must meet MIL-SPEC requirements including temperature ranges of -25-F to +125-F. Ground based radar systems such as THAAD or its expected follow-on make use of larger array sizes, both to increase radiated power and to improve discrimination capability.

4.1.2. Air

Platform sizes range from UAV's (and possibly micro-UAV's) to huge C-5 and C-17 aircraft. The desire to reduce the current large number of required emitters on each platform will drive designers toward multifunctional systems and generate pressing new device linearity requirements. Cooling is a problem on small platforms with dense apertures (especially apertures that must operate at millimeter frequencies). Efficient devices and heat removal techniques (packaging) are required. Aircraft self-protection systems are increasingly making use of towed decoys. Current UAV E/M systems generally can perform only single functions. Typically, a UAV platform must be returned to its base for re-outfitting whenever it is required to perform a different E/M function. If multifunctional systems can be developed that can affordably meet the performance

levels of multiple numbers of current single function systems, the necessity for re-outfitting would be eliminated and much more versatile and efficient sensor configurations could be realized.

4.1.3. SPACE

Satellite systems face harsh environments such as high levels of radiation and temperature and require the use of premium MIL-SPEC Class-S quality component devices. These devices are not replaceable in the field and, therefore, their operational lifetimes must exceed 5 to 7 years. Graceful system degradation and redundancy are preferable. Launch costs are high and the number of launch vehicles is limited. High efficiency is extremely critical, since it costs ~$10,000 per watt to place prime power into space. Principal RF functions performed are surveillance (radar) and communication. Radar apertures for earth observation are necessarily large. The requirement of large aperture size to meet mission requirements places serious demands upon missile lift capability. Weight and size considerations do not favor the use of conventional corporate-fed antennas. Agile E/M beams and beam-forming techniques must be used to avoid excessive energy on target. In applications where communication with and between satellites is required, needed performance will require improvement in linearity and phase noise over existing capabilities to allow effective use of new bandwidth-efficient signal formats such as m-ary QAM (quadrature amplitude modulation) and m-ary PSK (phase shift keying).

4.1.4. SEA

Large surface combat ships represent one of the best platform scenarios for application of multifunctional systems because of the current high number of independent emitters and the mutual electromagnetic interference they inflict upon themselves. Additionally the radar cross section of these multiple emitters is available for adversaries to exploit. Prime power limitations have generally not been a major consideration for ship borne systems. However, it may be an issue for future high power systems. Size and weight considerations are an issue only for TBMD applications. Cost of operation of a large number of single-function stand alone E/M systems is very high, thus, providing an additional incentive for implementation of multifunctional approaches using active apertures. Since systems used to perform radar, communications, electronic warfare and communications functions all require large amounts of power for their operation, heat removal is a serious challenge.

Over the next 15 years, the Navy plans to introduce active arrays into the fleet to perform most current radar and EW functions and to augment the capabilities of these arrays so that they can perform additional functions. The envisioned systems must be highly flexible, efficient, and affordable. For the longer term, the Navy is investigating the practicality of combining radar, communication and EW functions within a common active array aperture. A significant life-cycle cost advantage is anticipated, for newly built combatants, when it becomes possible to replace a large number of stand alone systems by a single multifunction system. The high power required for some radar and

EW missions imposes stringent cooling demands on systems. Achieving required isolation in a complex signal environment poses challenging linearity and filtering problems.

4.2. *RADAR NEEDS*

Historically, radars were designed for operation in the VHF/UHF portion of the RF spectrum. With technology maturation, various portions of the microwave and millimeter-wave spectrum have become increasingly used to perform radar functions. Presently, surveillance, acquisition, tracking, fire control and missile guidance use various frequencies ranging from below1 GHz through 94 GHz. These systems employ either SS or VE power amplifiers, depending upon the available technology options and specific system requirements. Relevant considerations dictating choice of a particular technology include power, bandwidth, system efficiency, life cycle cost (including operating and maintenance personnel, and component availability), maintainability, beam agility, reliability, noise, and linearity requirements. In addition, platform driven criteria also play a major role in the technology choice. Requirements for foliage penetration (FOPEN) are emerging at lower frequencies extending into the UHF portion of the spectrum and large fractional bandwidths are required. The Army's mortar and artillery location system, FIREFINDER (AN/TPQ-36 and 37), PATRIOT, the Navy's multi-function AEGIS radar, and the Air Force's surveillance radar, the AN/TPS-75, are legacy microwave systems. They are expected to continue in inventory and many will require upgrading and improvement since they will remain deployed well after their originally planned retirement dates. Emerging Air Force UAV systems, such as PREDATOR and GLOBAL HAWK, represent platforms that require sophisticated electronic antennas and automatic target recognition signal processing. Two dimensional electronically scanned arrays are preferred because they afford exceptional operational flexibility through the ability to independently control the amplitude and phase of each element. Spatial combining of array elements allows high ERP to be achieved.

Radar applications for millimeter-wave amplifiers include both tactical and instrumentation radars, missile seekers presently in use and planned future systems, MMW airborne radar for non-cooperative target recognition (NCTR) that use inverse synthetic aperture radar (ISAR) techniques, and weapons guidance systems which increasingly make use of millimeter-wave bands for enhanced all-weather performance. Many of these systems will require miniature apertures because of small missile diameters (4, 6 and 8 inch) as well as space and UAV requirements. Hence, compact mm-wave amplifiers will be required.

Realization of concepts to develop highly multifunctional systems including radars will reduce the Services' total number of systems along with associated components inventory and provide for much-reduced radar cross sections on the platforms that they are deployed on. They are also expected to reduce life cycle personnel, logistics and maintenance costs.

Though no longer on the Navy's Radar Roadmap, millimeter-wave tracking radar for ship self-defense, based on command guidance, has long been recognized as a potentially low-cost and highly-effective defense against supersonic low-flying anti-ship cruise missiles (ASCMs), especially as the last line of defense at very close range. Use of high-power millimeter-wave radar for performing discrimination functions in national missile defense applications is also receiving attention. Calculations and analyses by industry experts have shown that W-band discrimination radar can provide greatly enhanced performance against tactical ballistic missile penetration aids and countermeasures especially in the terminal sequence after decoy deployment.

The Navy Radar Roadmap illustrates that ballistic missile surveillance and tracking must be combined with traditional Navy missions of theater wide air defense and horizon search because of spatial constraints, beam resource management considerations, and the necessity to minimize radar cross section aboard ships. Fulfillment of the objectives of this roadmap will be completely dependent upon the successful development of multifunctional radar systems, using active apertures that meet required performance levels.

4.2.1. Airborne Radar

To provide better capabilities for detecting and tracking small slow moving ground targets under cloud cover or in high clutter sea or jamming environments increased phase stability over present capabilities will be required for UAV and other airborne radar surveillance systems. This tracking and detecting application is likely to require the use of active apertures. The three next-generation fighter aircraft, the JSF, the F-22 and F/A-18 E/F, will all employ multifunction X-band radar arrays. Emerging UAV systems such as PREDATOR and GLOBAL HAWK represent platforms requiring sophisticated power amplifiers as well as sophisticated electronic antennas and automatic target recognition signal processing. To increase the mission capability of UAV platforms such as these, which have limited payload capability, the use of multifunctional E/M active apertures is currently under consideration. Renewed interest in deployment of GMTI radar on UAV platforms points toward use of millimeter-wave amplifiers that operate in the Ka- through W-bands.

4.2.2. Ship-based Radar

The surface Navy has reached a consensus position to reduce the number of types of fleet radar systems from approximately 20 to 3 during the next 15 years. These three surviving radar suites will all be active aperture arrays. The first two, the Multifunction Radar (MFR) and Volume Search Radar (VSR), will perform self-defense and air control functions. Development of both of these systems is well underway. EDM is scheduled for 2002. The third radar suite is designed to perform the Theatre Ballistic Missile Defense (TBMD) function. It will operate as a suite of two apertures covering S-band and X-band. The full capability of this system is scheduled for IOC in 2016.

Upgrade of many of the Navy's ship-based radars to achieve required capabilities in the littoral environment and against TBM threats will require improvements in peak and average transmitter amplifier power as well as substantially increased phase stability to suppress the effects of clutter and jamming. In the longer term, multifunctional radar is expected to be combined with EW, and communication functions, sharing a common aperture. This multifunctional approach is expected to result in substantial life-cycle cost savings as well as enhanced protection from countermeasures. The former will be achieved through the reduction of personnel needed to operate and maintain the system; the latter through reductions in radar cross-section resulting from the elimination of the multiplicity of antennas and improved LPI radar waveforms.

4.2.3. Ground-based Fixed and Mobile Radar

The Army's current dominant mission is tactical battlefield maneuver. System improvements needed to successfully conduct this mission include upgrades of the AN/TPQ-47 Firefinder mortar and artillery location system, the SENTINEL Air Defense System, and the emerging Multi-Mode Radar (MMR) system. MMR will be used for battlefield surveillance and target location. Performance requirements dictate the fundamental architecture of these systems but size, weight, cost, and fielding schedule are crucial factors for deciding which technologies to use in Army programs.

Additionally, cost of ownership is a critical decision factor for Army radars, because their deployment near the front line of the theatre poses a high-risk of system loss or destruction. The USMC Multi Role Radar System contemplates the use of an active aperture. As the US Army increasingly becomes a lighter, more mobile force, it is anticipated that it too will integrate multiple radar functions.

4.2.4. Ground-Based Fixed Instrumentation and Surveillance Radar

The Air Force's Space HUSIR (Haystack Ultra-wide Band Space Imaging Radar) radar, presently proposed to meet Space Command mission requirements, requires amplifier technology capable of operating at a peak power level of >5 kW, 20% duty factor, and an 8 GHz instantaneous bandwidth.

Measurements of characteristics of ballistic missile intercepts at the Kwajalein Missile Range (KMR) rely on use of the millimeter-wave imaging radar system that is part of the Kiernan Reentry Measurement System (KREMS) on Kwajalein atoll. MIT Lincoln Laboratory has responsibility for operating and upgrading this radar for the US Army's, Space and Missile Defense Command. This range radar provides instrumentation for BMDO, Navy, and Army tests of both theater missile defense and national missile defense systems. Upgrading the Kwajalein Missile Range radar by equipping it with higher power, broader-band amplifiers for increased S/N on target as well as increased radar bandwidth, is needed for TBMD and National Missile Defense (NMD) evaluation. In Ka-band, the desired output power is 100 kW peak, 20% duty factor, with 4 GHz instantaneous bandwidth.

Air Force and intelligence missions require detailed imaging of orbiting satellites. The increasing miniaturization of satellites is making the space object-imaging (SOI) mission even more difficult. The US Space Command is currently engaged in discussions with MIT Lincoln Laboratory regarding an upgrade to the Haystack radar. The proposed upgrade calls for frequency of operation to be increased to W-band in order to provide dramatically enhanced SOI capability. No RF amplifier technology presently available can provide the 1 kW (average) and 5 kW (peak) power required for this upgrade over the 92 to 100 GHz band.

4.2.5. Missile Seekers

Missile seekers are decreasing in size. Current seekers have 4 to 8 inch diameters. Most now use mechanical antenna scanning techniques. However they require robust gimbals, especially those used in gun-launched smart munitions, where 18,000 G's of acceleration is a common occurrence. Operation at higher millimeter frequencies would offer the advantage of increased gain for the same aperture size. Smart munitions such as SADARM and BAT operate at Ka and W-band respectively. Smaller size (60 and 81 mm) munitions with increased capability are desirable and would require even higher frequency operation to achieve acceptable aperture gain.

4.3. *ELECTRONIC WARFARE NEEDS*

In recognition of the importance of Electronic Warfare (EW) to safeguard our nation's security, the U.S. House of Representatives has established its Electronic Warfare Working Group. This group provides oversight functions for this critical military thrust and operational area. An EW sub panel exists within the DoD RELIANCE structure under the SEEW Panel.

The value of active airborne electronic warfare systems was vividly demonstrated during recent action in Kosovo. There, the suppression of enemy air defenses (SEAD) played a key role in making it possible to sustain the air campaign, without loss of Allied force personnel. The Navy EA-6B PROWLER flew over 12,000 sorties in its support of this integrated air campaign, which utilized both Air Force and Navy assets. The Navy Analysis of Alternatives (AOA) assessment emphasizes the growing role of airborne standoff jamming from manned aircraft, combined with stand-in and escort jamming from UAVs.

The Tri-Service EW community has a continuing need for CW and pulsed transmitters capable of protecting aircraft, surface ships, ground vehicles, and other high-value platforms. Signal-to-jam (S/J) ratio or power-on-target are of fundamental importance. Powers of up to 200 watts (CW) and 2-5 kW (pulsed) over multi-octave bandwidths through millimeter-wave frequencies are essential for use in EW systems, almost all of which current employ 1-D (fan-shaped) E/M beams. Although these beams are beam-energy inefficient, they are cost effective for implementing single function systems. To operate effectively against agile–agile radars, future EW systems will likely use two-dimensional electronically steered beams.

The Navy's planned advanced NULKA shipboard decoy system is expected to be more energy-efficient than most current EW systems. Consideration is being given to the use of an active aperture, 2-D E/M beam concept to improve operating lifetime of the present system whose E/M beam is pointed by rocket engine vectoring of the entire platform. In future multifunctional system implementations incorporating EW, the concept of using a 2-D pencil beam with increased RF energy density may be possible. In addition, conventional narrow band noise jamming will be far less effective against future generations of wide band radars that employ advanced modulation technologies and future EW systems will require exceptional phase stability and linearity.

The Army's basic aircraft jamming systems, AN/ALQ-136 and AN/ALQ-162, are being upgraded as part of the Suite of Integrated RF Countermeasures (SIRFC) program. SIRFC requires wideband amplifiers for both the microwave and millimeter wave frequency domains. Air Force towed decoys have proven their worth in combat and have emerged as important candidates for upgrading. The Service's combat pilots have coined a phrase "don't leave home without one" as a measure of their acceptance of the security afforded by these towed decoy systems.

EW systems (e.g., AN/ALQ-211, towed decoys, IDECM upgrades, and UAV sub-systems) will be in inventory or development through 2025. For example, fielded AN/ALQ-162 and AN/ALQ-211 systems will be replaced with the SIRFC. It includes both RF and EO jammers that require RF amplifiers capable of small size, multi-octave bandwidth frequency coverage, high power, and overall high efficiency.

4.3.1. AIRBORNE SELF PROTECT AND SUPPORT JAMMING

Radar threat frequencies span a wide frequency range. However, they are usually known in advance. In addition to having wide bandwidth, RF transmitters must produce significantly higher effective radiated power (ERP) for longer standoff ranges, more effective jamming, and self-protection. Scalable (i.e., modular) transmitter architectures will support a wide variety of platforms, both manned and unmanned, requiring protection. In addition to higher ERP, these transmitters must have linearity characteristics that are suitable for arrays supporting polarization techniques, independent beam steering, etc. For UAVs, basic transmitter modules must be small and efficient. This will simplify RMA (Reliability / Maintainability/Availability) needs. Multifunctional RF systems are expected to be capable of increasing operational versatility of UAVs and UCAVs,. These systems will undoubtedly require advances in power amplifier technology, both VE and SS.

4.3.1.1 *2 TO 18 GHZ*

The most advanced new EW system is the AIEWS. It uses a planar array. To counter emerging threats, system linearity must be enhanced, output power increased, and high prime power efficiency achieved, all within a very small package. Far-term objectives for ultra wideband amplifiers (operating between 2 and 18 GHz) include 300 watts (CW), 46% prime power efficiency, -10 dBc 2nd harmonic power, and -160 dBc/Hz

@ 10 kHz offset in a 35 cu. in. package and costing $10/watt. These high power objectives are for 1-D array architectures only and do not presently apply to planar arrays that may be needed to address agile-agile radar threats of the future.

4.3.1.2 *18 TO 40 GHz*

Emerging new applications in the millimeter wave spectrum pose serious problems for electronic attack as this part of the RF spectrum becomes increasingly important for military communications, missile seekers, and radars. Near term needs must provide building-block power of 100s of watts (CW) coupled with acceptable prime power efficiency. Suitable amplitude / gain / power and phase tracking characteristics for supporting advanced array architectures are also necessary. Far-term objectives for (18 – 40 GHz) amplifiers are 200 watts (CW), 38% prime power efficiency, -20 dBc 2nd harmonic power, ±10 deg phase tracking, ± 1 dB gain tracking, ±1 dB power tracking in a 40 cu. in. package at a cost of $30/watt. To operate against sophisticated new radars that employ orthogonal modulation techniques, future amplifiers must incorporate much greater phase stability and linearity than in the past. If in the future millimeter wave EW system architectures migrate to active aperture planar arrays, as is the case for the latest microwave systems, power requirements will be reduced for each elemental amplifier.

4.3.2. SHIP-BORNE AND GROUND-BASED SELF PROTECTION

As is the case for airborne platforms, radar threat frequencies occur over wide frequency ranges but are known in advance. Future radars will exhibit much greater frequency diversity. In addition to having wide bandwidth, terrestrial-based RF transmitters must produce significantly higher ERP (to protect larger platforms) to effect required longer standoff ranges, provide more effective jamming, and better self-protection. Scalable (i.e. modular) transmitter architectures will support a wide variety of platforms, including both manned and unmanned vehicles that require protection. In addition to higher ERP, transmitters must provide a level of linearity that is suitable for arrays supporting polarization techniques and independent beam steering.

4.3.2.1 *2 TO 18 GHZ*

All of the enhancements described in section 4.3.1.1 will also be required for ship-borne and ground based self-protection applications. The Navy is funding a study to determine whether an advanced NULKA stand-off EW deception missile can be configured as an active aperture array with beam pointing/steering capability, instead of relying on rocket engine power to point the missile and its fixed antenna as the present NULKA system does. Power requirements per amplifier for the advanced NULKA array of many amplifiers would ideally be much smaller than for the present system and proportional to the number of amplifiers to be used (yet to be determined).

4.3.2.2 *18 TO 40-GHZ*

The comments in section 4.3.1.2 apply. If ship-borne and self-protection systems, operating at millimeter wave frequencies are incorporated into multifunctional systems or become 2-D systems, then active aperture arrays will predominate. Affordability issues will ultimately determine if 2-D arrays become viable.

4.4. *COMMUNICATIONS*

The DoD is evolving from a platform-centric to a network-centric force structure. Under this new vision, networked sensors and weapon systems will provide increased superiority in the battle-space environment through greater information dominance, improved timeliness of action, and enhanced accuracy and precision of actions. This network-centric orientation relies heavily on the availability of high data rate (HDR) communication systems and their underlying technologies. A recent study by DISA projected a need for 10 Gbps of SATCOM capacity by 2010. In Joint Vision 2010, the Defense Science Board Task Force on tactical battlefield communications concluded that an aggregate capacity of 35 Gbps would be required to simultaneously support two major theaters of war. This requirement poses a major challenge to the system designer. It can only be met in a cost-effective manner by achieving higher performance from the technologies utilized in these future communication systems.

The ability to achieve dramatic increases in future HDR communication capabilities is confounded by the lack of available spectrum during periods of time other than wars. In the near- to mid-term, increasing DoD capacity needs can be met through the use of more spectrally efficient digital modulation techniques that require RF power amplifiers with increased linearity and improved phase noise. In the longer term, the quest for higher data rates may be better met by migration to the wider allocation bandwidths found at the millimeter-wave frequencies. Obviously, power amplifier technology must be improved to keep pace with the stringent system performance demands; improvement in power output must be coupled with improvements in quality of performance (e.g. bandwidth, efficiency, linearity, phase noise, low distortion). The diversity of platform and performance requirements necessitates the development of both improved VE and SS amplifier technologies.

Regardless of platform specifics, albeit with varying degrees of emphasis, future systems will require high power, wide bandwidth, high efficiency, improved phase stability, and low distortion, from a compact transmitter. New broadcast systems will require substantial increases in operating power, linearity, and efficiency without suffering a reduction of reliability. Versatile new systems employing beam pointing and footprint diversity require inherently superior phase stability. Carrier-to-third-order intermodulation products (C3IM) of –80 dBc are needed in the near term; –100 dBc is needed for the long term.

The need for vastly greater data connectivity, in the 21st century, is placing greater demands on RF communication links. Their operating frequencies are migrating

rapidly into the millimeter-wave band. Aperture size constraints on shipboard platforms, frequency allocation restrictions in the microwave band, and increasing pressure on the government to allocate existing spectrum to commercial applications, is pushing the military to frequencies well above traditional SATCOM bands. The Air Force's MILSTAR system, including the Army's SMART-T terminal and the planned Advanced EHF satellite constellation, operates in the millimeter-wave band. Although many satellite links may be either RF or optical, the need for all-weather connectivity among mobile platforms on land, in the air, and at sea, mandates that RF systems be a major part of the overall communication system architecture. Better spectral utilization is clearly necessary and there is an opportunity to increase this by the use of emerging bandwidth-efficient m-ary signaling formats. For all communication systems, wide analog bandwidths, much improved linearity and phase stability, and high average power are required in order to support increasingly high transmission data rates (HDR) achieved with complex m-ary signaling formats.

Terrestrial communication systems operate at frequencies between 30 MHz and several GHz. The Army's Joint Service Tactical Radio covers the 30 MHz to 2000 MHz portion of the spectrum. It uses advanced modulation techniques as well as software programming to achieve anti-jamming operation. Extremely efficient power amplifiers operating at low voltages with high linearity, power recovery circuits and low intermodulation distortion will be required to meet 21st century battle-space requirements. The Army's Future Combat Vehicle (FCV) and the Navy Network Centric Warfare programs will both require extensive networking communications systems and protocols to be effective. Navy ships will require multifunctional active aperture based communications in order to meet radar cross-section requirements. To meet HDR requirements, however, even greater power (within the limited bandwidth available) must be provided with much better linearity, reduced gain ripple and reduced phase ripple. Alternative approaches to increased HDR include much improved phase stability.

Increasingly, satellite communications systems used by the military will demand multiple simultaneous footprint beam pointing and beam shaping capability. Implementation of these types of systems will force the use of active aperture, electronically scanned antennas to permit different information transmission in each beam.

4.4.1. Ground Segment

All Services require ground- or ship-based terminals for satellite systems. The U. S. Army's Secure Mobile Anti-Jam Reliable Tactical Terminal (SMART-T) is a MILSTAR-frequency (43.5- to 45.5 GHz) uplink. The goal of achieving 100% link availability with a 10 Mbps data rate presently requires a transmitter power of 75 to 80 watts. The transmitter package volume is limited. The presently used transmitter provides only 25 to 30 watts of power and consequently experiences difficulties in link closure under adverse weather conditions. While an array could provide ample power and

S/N ratio, its added cost may render it unacceptable, unless the system is required to communicate simultaneously with more than one satellite. Powers needed in the near term for ground segment systems are 500 W @ 50% efficiency in the 3-12 GHz bands, 100 W @ 50% efficiency in the 30-45 GHz bands, and 50 W @ 40% efficiency in the 50-65 GHz bands. In the 90-110 GHz and 130-160 GHz bands, 50-100 W at 20% efficiency or higher is needed. Mid- and long-term needs are for 3 dB to 6 dB more power than this to satisfy both ground and airborne relay node needs. Power requirements for active aperture arrays that employ multiple simultaneous signals are much lower.

4.4.2. Space Segment

Relevant platforms include the Air Force's space segment, with MILSTAR and planned Advanced EHF, Wideband Gap Filler, and GPS III satellite constellations as well as the Navy's Advanced Narrow Band System/Mobile User Objective System. The continued development of power amplifier technology with renewed emphasis on improved linearity, lowered phase noise floor, improved efficiency, and increased power capability in the conventional SATCOM bands is needed. For revolutionary micro-satellite applications ultra-compact high power transmitters need to be developed.

4.4.3. Cross-Links & Relay Nodes

Cross-links of satellite constellations, operating in the 50 – 65 GHz frequency range, must also support the higher data rates. In the near term, a power output of 75W with 55% power added efficiency is required. In the far term, 500 W with 50% power added efficiency will be required. New highly efficient, high power laser-based systems may provide significant competition to RF. In the quest for capacity, operating frequencies even higher than V-band have been envisioned for some future communication networks such as UAV-based relay nodes. Communication relay by UAV is to be an increasingly important mission. If the UAV is to simultaneously perform other functions, a multifunctional active aperture array may be a better choice. Whether for theater-wide over-the-horizon communications, or as relays for HDR ground-to-space links, UAV payloads have strict size, weight, efficiency, and prime power requirements. For future systems, the use of high-order digital modulation will require optimization of the efficiency and phase stability of transmitters within tight linearity constraints.

4.5. *MULTIFUNCTIONAL ELECTROMAGNETIC SYSTEMS*

Multifunctional electromagnetic systems combine into one aperture the functions that would otherwise require several apertures. This integration significantly reduces the radar cross section (target size) of the platform on which it is installed. Multifunctional systems also greatly reduce the need for training operators and maintenance technicians for diverse systems and greatly reduce the logistics required to service the electromagnetic suite. The combination of personnel and logistics savings is expected to easily provide life cycle cost savings equal to the initial cost of the equipment. With the advent of direct digital synthesizers operating in the microwave spectrum, still another

advantage accrues: as changes in operational requirements appear, the functionality of systems can be upgraded by software upgrades rather than by the development and installation of new hardware. By bringing digital technology closer to the antenna, it may be possible to significantly increase system efficiency and further reduce distortion in the power amplifier chain.

By definition, multifunctional systems must be capable of transmitting multiple simultaneous beams of RF energy. To be fully effective, each beam must be given independent control regarding bearing, elevation, frequency, power, modulation, and beam shape. An example of a multifunctional electromagnetic system is one that performs the integrated functions of theater air defense, horizon search, and ballistic missile defense radars through the same aperture. The Navy currently has radars that perform more than one function, but they do so in a time-shared manner. This is not acceptable when large volumes of space must be searched. Another example of multi-functionality is the integration of communications, radar, and EW capabilities such as will be required on future ships. The ability to simultaneously perform these functions using a single system would also significantly increase the operational and mission capabilities of UAVs and UCAVs. Still other examples are the USMC multi-role radar system and the Army's Rotman-lens-steered millimeter wave systems. With the advent of composite airframe structures, conformal multifunctional apertures will become available on aircraft as well.

Multifunction systems represent an important new approach for reducing the number of apertures on a platform and/or the cost of the combined system over a collage of single function systems. The Navy's Advanced Multifunction Radio Frequency (AMRF) concept combines EW, Radar and Communication functions into one aperture while the Army's Multi-Mode Radar (MMR) combines artillery, air defense and TMD surveillance functions.

21st century surface combatants will increasingly demand multifunctional systems for a variety of reasons. All will require agile, active aperture electronically scanned antennas with multiple, simultaneously steerable beams. They are also likely to gain the advantages of being able to perform target tracking, target illumination/missile command and guidance, and EW functions using a single beam that can operate against any given target. As composite airframes come into existence, conformal multifunctional apertures will also begin to appear on aircraft.

The architecture of any military electromagnetic system must simultaneously deliver required performance (e.g., ERP, resolution, linearity, beam agility) at an affordable acquisition cost (e.g., affordable RF transmitters and components, non-complex beam pointing techniques) without adversely impacting the survival of the platform (e.g., minimizing IR signatures, stealth). The trend in system architecture has been, in general, toward phased arrays over the past several decades, and toward active phased arrays, in particular. For wideband multifunctional systems requiring simultaneous beams, incremental time delay beam steering techniques must be used. Multifunctional systems must also be capable of vertical, horizontal, and circular signal

polarization. This requirement sets rather severe physical size constraints on the microwave amplifiers used with each antenna element as two such devices are generally required for each half-wavelength.

The Army's emerging, highly-mobile, lightweight, flexible Future Combat System (FCS) RF systems represent a significant challenge for the system architecture designer. FCS will require that radar, communications, and electronic warfare functions be collectively performed at performance levels currently available from individual tactical systems in inventory. Combining multi-modes and multi-function capabilities in a single system has considerable merit in situations where platforms are large enough to accommodate the desired configurations.

5. PERFORMANCE AND SYSTEM ARCHITECTURE ISSUES THAT DIFFERENTIATE APPLICATIONS AND TECHNOLOGY GAPS

It is the responsibility of the DoD electronics S&T community to continuously assess electronics technology status, new electronics developments and military system needs to assure that our warfighters have the benefit of highly competent electronic systems to assist them in carrying out their critical missions. Consistent with available resources, the electronics S&T community crafts a strategy for judiciously investing the electronics S&T budget. Its principal objectives are to advance the performance, reliability, availability and affordability of materials, devices, integrated circuits and components based on either existing technologies or on promising new technologies that are germane to DoD applications. Electronics technology is so important and so pervasive in DoD weapon systems that it can accurately be described as the primary factor for providing our military personnel with a technological edge over our adversaries.

Any particular system design team will necessarily make informed choices among the array of component technologies available to them at the time. Systems designers will also look for paradigm shifts made possible by emerging new technologies. However, the set of component choices for one given system should not imply that a different design team, planning a different system, for a different Tri-Service or DoD requirement, on a different timetable, will necessarily select the same set of components for implementation of their system.

Examining the wide variety of performance metrics of even one type of component, the RF power amplifier, can highlight the complexity of the system trade-off process across all components, and correspondingly, the fallacy in making sweeping generalizations about technologies. For the RF power amplifier, a specific performance metric may or may not be important for a given system (radar, EW, communications, smart weapon). Selection of the critical performance metrics is also highly dependent upon both the intended system mission (e.g., mobile tactical radar versus fixed instrumentation radar or disposable vs. non disposable) and the specific architecture of that system. The choice of aperture type (parabolic dish, passive array, or active aperture) and size is often the most important variable influencing the amplifier power

requirement. This parameter can vary by many orders of magnitude. In the past, the only viable source of RF power generally dictated use of a corporate fed array; today, an active aperture array can offer performance, reliability, and cost advantages for many applications. The wider issues of system tradeoffs and affordability are addressed in the subsequent section. Some further understanding of the complex factors dictating a particular choice of power amplifier may be gain by analysis of a generic mission platform and its environment. Some short comments will be made about each.

5.1. *POWER – BANDWIDTH*

For new and upgraded electronic attack (EA) systems, wide bandwidth is the prime requirement since threat frequencies may not be pre-determined, and flexibility of response is required. In the future, additional requirements of increasing importance are those of high phase stability and linearity. These will enable the deception of next generation radars that employ sophisticated modulation formats. Currently, no amplifiers of any kind exist that are capable of accomplishing this objective. For single function EA systems, employing 1-D fan-shaped beams, multi-mission amplifiers, such as the MPM and MMPM, reduce unit cost. Use of WBG driver amplifiers may allow meeting the stringent requirements for high phase stability and linearity. The unexcelled ability of VE amplifiers to deliver large amounts of RF power across wide bandwidths at microwave and millimeter-wave frequencies with low distortion and high efficiency makes them cost effective for use in 1-D systems. As threats become more advanced, the need to use 2-D pencil beams drives architectures toward active apertures. In laboratory tests, multi-octave, all solid-state WBG power amplifiers have already demonstrated output power levels that are a significant percentage of those of fielded MPM units but at lower efficiencies. However, MPMs will also take advantage of advances in SS amplifier technologies to increase their power output and efficiency by improved power partitioning between the driver-stage solid-state amplifier and the output-stage vacuum tube booster.

5.2. *EFFICIENCY*

Vacuum, in contrast to solid-state materials, provides essentially ‘collisionless’ transport. In addition, the technique of multi-stage depressed collection allows a VE system to recover spent beam energy, i.e., beam energy not converted to RF power. Together, these attributes of VE amplifiers provide DC - to - RF efficiencies that may be a factor of two higher than that of high power SS amplifiers for comparable instantaneous bandwidth and power output specifications of single amplifiers. However, since the overall system efficiency is the ultimate metric of interest, architectures that minimize RF power distribution loss (i.e. active aperture over corporate feed systems) can have superior overall efficiency even though individual amplifiers may have lower efficiency in the active aperture array. Trade offs concerning power, linearity, and high phase stability must also be considered for both solid-state and vacuum electronic amplifiers. As modern E/M systems increasingly adopt dynamic power management strategies, energy is conserved by reducing transmitted power, whenever possible. Both VE and SS

technologies make use of advanced design techniques for achieving highly linear operation. A high degree of linearity usually depends upon power scaling. Advanced modeling and simulation methods may lead to improved VE devices that can circumvent the use of power scaling for realizing highly linear operation. Similarly, new high power digital amplifier technology, currently under development, may enable SS technology to gain the combined benefits of a high degree of linearity and high power added efficiency, without the need for power scaling. Future UAVs will increasingly become multifunctional. This will lead to the necessity for using multiple simultaneous beams for transmission, thereby making SS technology increasingly competitive with VE. With the advent of WBG semiconductor devices and their large dielectric strength, highly linear, highly efficient, highly phase stable, high power amplifiers (such as Class B push-pull) are beginning to be developed. If these types of amplifiers can be successfully implemented, they will compete effectively with VE devices in power and bandwidth and may surpass them in phase stability and linearity. This is expected to be particularly the case for amplifiers exhibiting greater than an octave of bandwidth. For EA applications, any additional signal delay is to be avoided. Here the self-gating Class B, push-pull (or complementary amplifier) has a distinct advantage over VE devices because the signal itself turns on the amplifier and, as a result, the amplifier dissipates negligible power in the absence of a RF signal input. Finally, for those designs that use array architectures, total transmitter efficiency will be influenced by losses in the RF power distribution and network phase shifters. Corporate fed arrays require control components to split and distribute RF power. Active arrays that have a power amplifier at each radiating element do not require these additional control components. As a consequence, distribution losses in corporate fed arrays will be higher than those of active arrays. For example, the Navy's Aegis system uses a corporate fed array architecture. Its RF power loss between the VE amplifier and any given antenna element is on the order of 2.2 dB. For an active array, implemented with SS power amplifiers, this loss is generally reduced to a fraction of a dB.

5.3. *FREQUENCY*

High RF power at frequencies above 25 GHz (>10's of watts) is currently provided exclusively by VE. The reason for this is the rapid fall-off in $P\text{-}f^2$ for solid-state devices at these frequencies. Single function, corporate-fed, passive array or parabolic dish applications requiring significant power at millimeter-wave frequencies currently have no alternative to the use of VE devices such as coupled-cavity TWTs or fast-wave amplifiers (e.g., gyroklystrons or gyro-TWTs). Where active arrays are required for multifunctional applications or for radar cross-section reduction, SS devices can compete with VE devices at frequencies up to at least 45 GHz. However, affordability will remain an issue.

Currently about 90% of the E/M systems on DoD platforms operate at frequencies below 45 GHz. However, as demand for increased data rates increase, it will be necessary to make use of the only available remaining spectrum, which is above 45 GHz. Alternatively, spectral utilization efficiency of present military frequency allocations could be increased significantly (this increase will probably be limited to 11 dB because of atmospheric scintillation effects). One way of accomplishing this is through the use of

more sophisticated modulation techniques. These are more demanding of highly linear power amplifiers and a high degree of phase stability. Heterojunction bipolar transistors (HBTs) demonstrate unsurpassed phase noise characteristics. A second choice with phase noise characteristics that are almost as good are pseudomorphic high electron mobility transistors (PHEMTs)

5.4. *ARRAYS*

Active phased arrays requiring half-wavelength element spacing can be implemented using small-cross-section VE power boosters, at frequencies up to X-band. For applications requiring both vertical and horizontal polarization, VE devices generally can be used only at frequencies half as high because two amplifiers will usually be required behind each antenna element. This is particularly true of antenna apertures required to perform 2-D pencil beam EA functions. To date, there are no systems fielded or under development that employ VE in fully populated 2D active array. Operating VE amplifiers below saturation to ensure acceptable linearity and harmonic distortion reduces their efficiency. Research is being performed to overcome this drawback with the aid of modern modeling and simulation methods. SS amplifiers operating at power outputs well below their saturated level pay similar efficiency penalties. However, new high power digital amplifiers, currently under investigation, may not suffer from this drawback. Although the size of SS modules makes them attractive for active phased arrays, their relatively low power and high cost could require the use of alternative VE approaches particularly in certain single function systems providing that VE manufacturing costs can be substantially lowered. One approach that would enable VE devices to operate in 2-D arrays at much higher frequencies is to sparsely fill the aperture so that the VE amplifiers can physically fit within the required dimensions. This approach, however, reduces the scanning capability of the antenna but may be appropriate for certain applications for which the direction of the threat is constrained to a reduced solid angle. This approach is not likely applicable to highly mobile platforms as the available scan angle for a sparse array is considerably less than that for a fully populated array.

Solid-state	Vacuum Electronics
• As threats become more advanced, the need to use 2-D pencil beams drives architectures toward active apertures. In laboratory tests, multi-octave, all solid-state WBG power amplifiers have already demonstrated output power levels that are a significant percentage of those of fielded MPM units although with lower efficiencies. • The necessity for using multiple simultaneous beams for transmission will make SS technology increasingly competitive with VE. • With the advent of WBG semiconductor devices and their large dielectric strength, highly linear, highly efficient, highly phase stable, high power amplifiers (such as Class B push-pull) are beginning to be developed. If these types of amplifiers can be successfully implemented, they will compete effectively with VE devices in power and bandwidth and may surpass them in phase stability and linearity • For multifunctional applications or for radar cross-section reduction, SS devices can compete with VE devices at frequencies up to at least 45 GHz. However, affordability will remain an issue. • Heterojunction bipolar transistors (HBTs) demonstrate unsurpassed phase noise characteristics. A second choice with phase noise characteristics that are almost as good pseudomorphic is high electron mobility transistors (PHEMTs).	• For single function EA systems, employing 1-D fan-shaped beams, multi-mission amplifiers, such as the MPM and MMPM, reduce unit cost. • The unexcelled ability of VE amplifiers to deliver large amounts of RF power across wide bandwidths at microwave and millimeter-wave frequencies with low distortion and high efficiency make them cost effective for use in 1-D systems. • MPMs will take advantage of advances in SS amplifier technologies to increase their power output and efficiency by improved power partitioning between the driver-stage solid-state amplifier and the output-stage vacuum tube booster. • VE devices provide DC - to - RF efficiencies that may be a factor of two higher than that of high power SS amplifiers for comparable instantaneous bandwidth and power output specifications of single amplifiers. • High RF power (>50 W) at frequencies above 25 GHz is currently provided exclusively by VE. • Dual polarization, active phased arrays requiring half-wavelength element spacing can be implemented using small-cross-section VE power boosters, at frequencies up to X-band. However, affordability may remain an issue.

Table 5.1. Summary of Advantages and Disadvantages of VE and SS Devices.

6. TECHNOLOGY ALTERNATIVES, S&T CHALLENGES AND OPPORTUNITIES

In the frequency range of interest for most military radar, electronic warfare, and communication systems, (~100 MHz to 140 GHz), RF power generation and amplification is provided by both SS and VE technologies. Both technologies have a long heritage of device advancement over the past half century. From the 1930's to the 1960's, vacuum electronics, in the form of a variety of device types, was the only technology capable of meeting the power performance requirements of military systems. The birth of modern vacuum electronics may be associated with several discoveries and technology advances, among them the invention of the helix TWT, the development of the dispenser cathode, and the implementation of simple metal/ceramic packaging. These developments took place in the late 1940's and early 1950's, during the same time period as the invention of the transistor. With the invention of the transistor in 1948, solid-state amplifier technology evolved rapidly under the stimulus of military and commercial pressure. By the late 1960's, solid-state technology began to provide the military system designer with a viable alternative RF power amplifier technology, for some applications. Since that time, DoD advances in GaAs materials, devices, and circuits have led to the presently fielded solid-state array transmitters. The power and bandwidth performance of VE amplifiers has also advanced during this time period, and VE is used in most present-day fielded radar, communications and EW systems.

Since the 1960s, both technologies have continued to evolve in performance to meet DoD system needs. Recent trends in SS amplifier technology are marked by continuing improvements in the more common Si and GaAs-based devices and integrated circuits, as well as recent advances in devices and integrated circuits made from WBG semiconductor materials. These advances are providing the technology base for a wide variety of new E/M systems. Recent trends in the area of VE devices include the development of compact high power microwave power modules (MPMs) and high power millimeter wave amplifiers.

The single device state-of-technology, characterized by average power versus operating frequency is shown in Fig. 6.1. In 1960, Nergaard proposed average power per unit frequency squared as a figure of merit providing an insightful basis for comparing (VE) device types and portraying trends in performance growth. E.O. Johnson subsequently presented similar arguments for SS devices. The physical significance of $P_{av}f^2$ as a figure of merit derives from the fact that the maximum beam or charge carrier power that can be transported through a device is proportional to the circuit cross-sectional area, which is inversely proportional to the operating frequency. Upper limits in power density were therefore considered as intrinsic to a device design. Since the power density of WBG transistors is up to ten times that of silicon, GaAs, or InP transistors, their cross section can be greatly reduced at a given power level and the upper operating frequency greatly increased. Alternatively, at a given operating frequency, in principle, the power per device can be greatly increased over that obtained with traditional materials. Examples of recent impressive performance results from WBG devices are as follows: at 10 GHz, a power density of 11.1 watts per mm of device

periphery was achieved. This compares with 0.8 watts per mm achieved from GaAs devices. Maximum SS device power, at 10 GHz., has jumped from less than 20 watts to 50 watts (laboratory result) at 10 GHz.

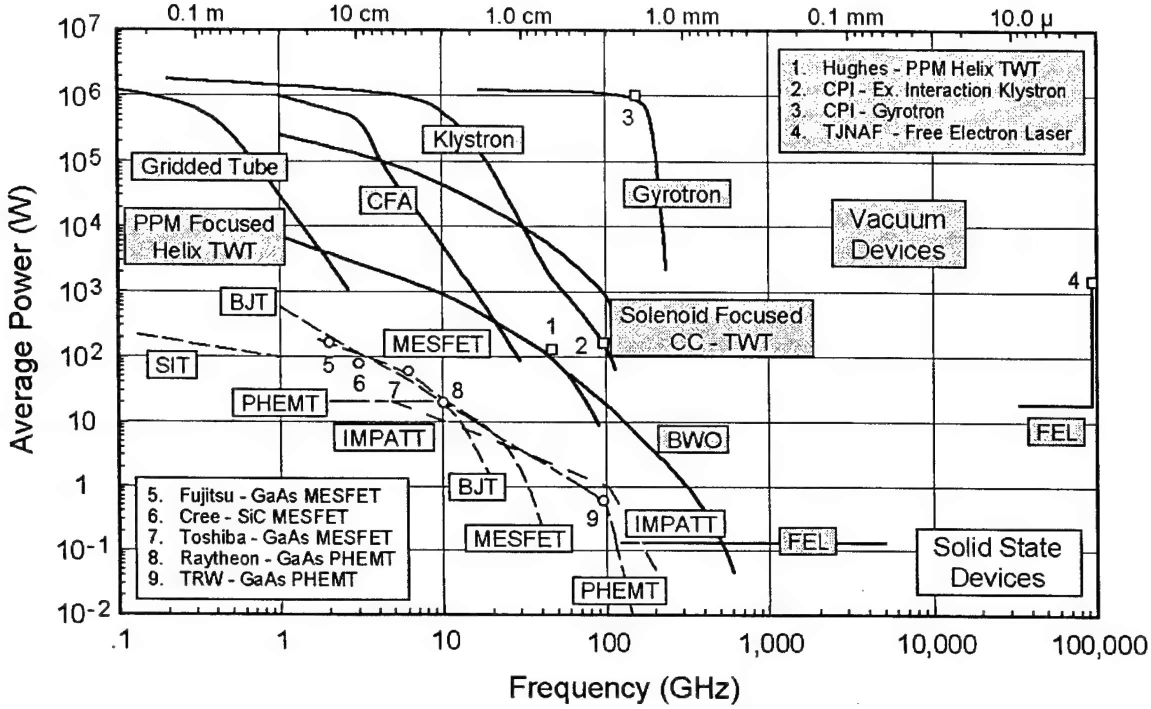

Fig. 6.1. Present state of device technology.

While Figure 6.1 portrays a significantly higher device power available from vacuum electronics versus solid-state technologies, it is important to note that device power alone is not the sole determining factor for system applicability. Factors such as effective radiated power, power aperture product, instantaneous system bandwidth and beam versatility are also important. These system factors are largely influenced by architecture and while the architecture drives the amplifier requirements, the performance available from the amplifiers also drives the architecture. The trade-offs are not always obvious.

An overlay of DoD system architecture directions onto the technological capabilities of both VE and SS is shown in Fig. 6.2 for the case of active electronically scanned arrays (AESAs). The continuing evolution of military system architectures creates challenges that must be addressed for both technologies. For most modern active phased array radar applications, the required average power per radiating element is in the 10 to 1 kW range over frequencies from 1 GHz to 10 GHz. Required peak power is also in the 10 W to 1000 W range per radiating element. System architectures based on phased arrays have numerous advantages over traditional single feed-point antennas for many missions, including agile high-speed beam steering for the engagement of multiple simultaneous targets and the ability to place antenna pattern nulls at the location of hostile jammers. These architectures require amplifier technologies in the power-frequency region labeled "Performance Domain AESA Single Element" in Fig. 6.2. For

these applications, the state-of-technology as presented on a P_{av} vs. frequency plot is only relevant to the extent that it meets the form-factor requirements and the power-per-element requirements of the array architecture.

SS technology is a natural fit to active array architectures, but for some future array designs, present Si and GaAs solid-state technology has insufficient power per element (at a specific efficiency and bandwidth) to meet requirements. For this reason, both SS technology and VE technology are in need of advances to meet the needs of these future system architectures.

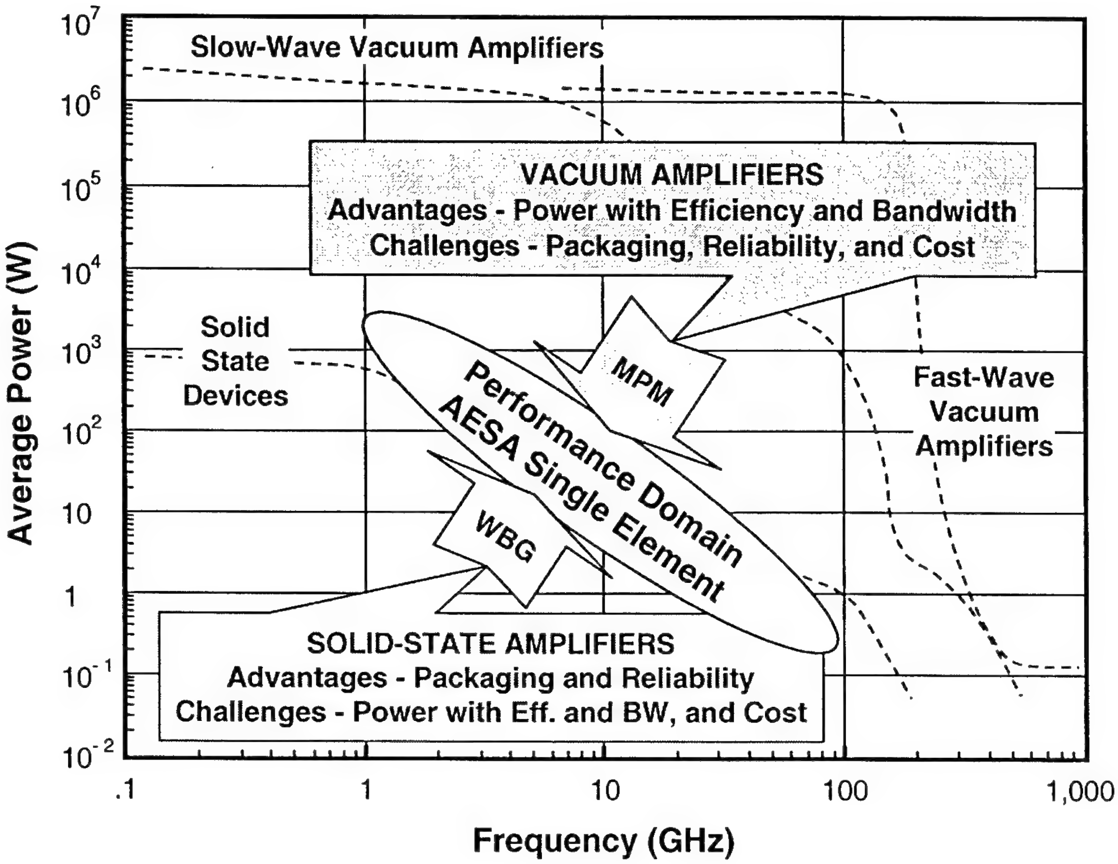

Fig. 6.2. Source Options for Active Electronically Scanned Arrays (AESAs) at the single element unit

Principal challenges for SS technology to meet future DoD active phased array system architectures include increased single device power, increased device efficiency, and reduced cost. Although present day SSPAs are well suited to active array architectures, their single device power remains below that needed for some applications. For this reason, advances in power per device which is afforded by the development of WBG technology is an important direction for the technology, and promises dramatic advances in the capabilities of future active arrays based on this technology.

Principal challenges for VE technology, to meet future DoD active phased array system architectures, include reduction of device size in order to fit evolving DoD system architectures and unit cost. An imperative for pushing VE devices in this direction is their ability to produce large amounts of power efficiently. New VE devices and device concepts must be compatible with the new active array architectures or their unexcelled ability to produce power and wide bandwidth at high efficiency will be incompatible with them. DoD cannot afford to miss the opportunity to push VE technologies in this direction, as the technology provides a critical backup to the development of WBG semiconductors for those array applications requiring high power and wide bandwidth per radiating element. Consequently, even for those DoD system architectures where active arrays are the only viable solution, the continued development of VE technology, such as the MPM, provides an important means of risk reduction.

Albeit an attractive and vitally important architecture for many DoD systems needs, active phased arrays are by no means the only architecture that will best satisfy all DoD system requirements. Both performance and cost considerations require the use of alternative system architectures to meet some DoD mission objectives. In many cases, even for new systems, conventional parabolic antennas and passive arrays are used when it is appropriate to do so. Examples abound of use of VE and of SS and of varying architectures for meeting the needs of numerous DoD applications. For example, SSPAs and MPMs are both under investigation for use in the Army's SMART-T terminal. VE amplifiers and SiC PAs were both considered for us in the TPQ-47 Firefinder passive array radar. Still other specialized applications clearly dictate the selection of one technology over the other. For example, ground-based instrumentation and surveillance radars frequently make use of single feed-point parabolic antennas. Thus, these systems are well suited to the use of high power VE technology, unconstrained by the packaging restrictions of active arrays.

Both VE and SS technology continue to show advances in technological performance of relevance to DoD systems. Both technologies have achieved impressive levels of device performance and both technologies have opportunities for continued advances in directions of importance to the wide variety of system architectures under consideration for present-day and future DoD system designs.

6.1 *SOLID-STATE TECHNOLOGY*

Solid-state technology currently is the technology of choice for virtually all RF receivers and many power RF transmitters. Where aperture size is relatively unconstrained, GaAs (the current baseline material for solid-state devices) devices and integrated circuits (MMICs) also compete well for use in certain high-radiated-power applications (e.g., the Army's THAAD and its follow-on and the Navy's MFR). GaAs technology has been brought to a high level of maturity through the completed DoD initiatives known as the MIMIC and MAFET programs. However, GaAs technology will not meet many future RF DoD application requirements because of both its performance limitations and affordability considerations. Recent R&D has demonstrated that superior solid-state RF performance may become available from amplifiers based upon SiC and GaN semiconductors. Packaging and heat removal from RF electronics continue to represent challenges as system sizes shrink without commensurate reduction in power density requirements. Energy consumption (device efficiency) limitations represent particularly difficult challenges for portable systems such as the Army man pack and for special platforms such as the Air Force's space platforms.

6.1.1. STATE OF TECHNOLOGY

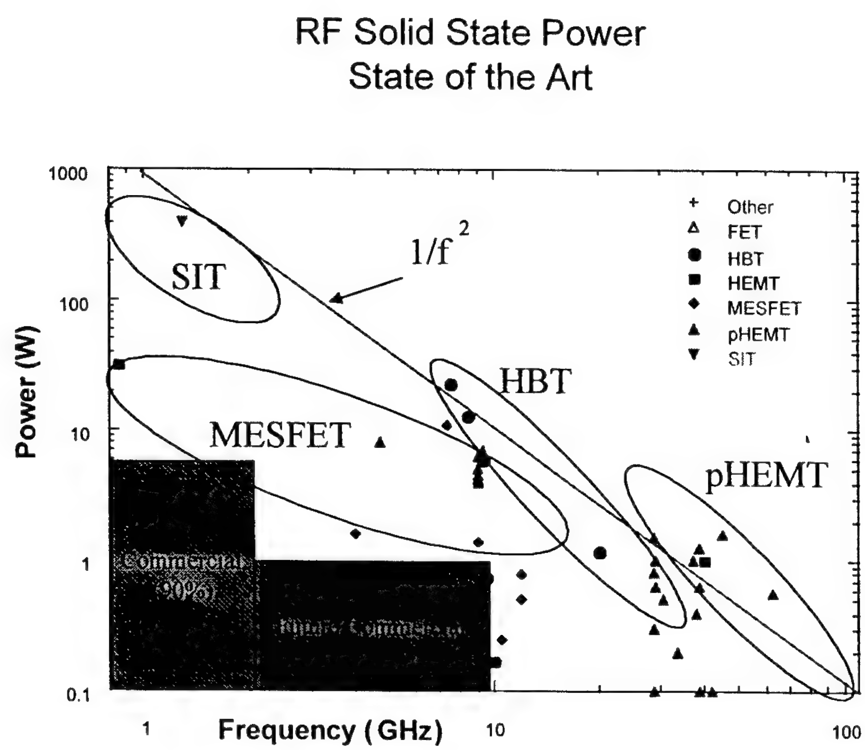

Figure 6.3. RF Solid-state Power State of the Art

The state of the art for RF solid-state technology is presented in Figure 6.3. Gallium Arsenide based transmitter technology has reached a level of maturity at which power output, bandwidth and efficiency are nearly at their theoretical limits and are now increasing quite slowly with time. This maturity level has been achieved over the past 20 years, largely as a result of substantial DoD investments, including those for the DARPA MIMIC and MAFET programs, which totaled approximately $750 million. This technology has enabled modern active aperture phased array transmitter systems that are only now in the initial stages of system insertion. These include the F-22 and JSF fire control radars, and the THAAD Ground Based Radar System. GaAs MMIC amplifiers are also the baseline approach for MFR shipboard area defense radar and the AN/SLY-2 EW transmitter, which are scheduled to be fielded within the decade. The major remaining challenge for this technology is cost reduction. Performance specifications mandated by DoD requirements, for example, those for a X-band radar system, currently stress the performance capabilities of GaAs technology. The resulting low level of yielded devices capable of meeting the performance criteria for this type of system results in costs of typically $500-$1000 per T/R module with about a third of the cost being in the GaAs components of which the high power SS MMIC amplifier is ~$100. By contrast, the GaAs component content of commercial based modules having lower performance requirements may be produced for just a few dollars as a result of much higher manufacturing yield and smaller dies size. The output impedance of WBG devices is considerably higher than that of GaAs devices, thus making it potentially easier and more efficient to combine output power from these devices and also easier to obtain broadband operation. WBG devices also require much less semiconductor surface area per unit power output than their GaAs cousins. Commensurate cost reduction is anticipated assuming that costs of large area substrates can be sufficiently lowered and high yields can be achieved.

Indium Phosphide technology is increasingly becoming the solid-state technology of choice for higher frequency RF (millimeter wave) applications (up to 100 GHz). It is also an enabling technology for ultra high efficiency transmitters (60-90% PAE) in the microwave frequency range. The highest performance millimeter wave devices (HEMT) are produced on InP substrates or on metamorphically-buffered GaAs substrates (M-HEMTs). These technologies, although under development for about 15 years, have only recently reached a level of maturity approaching those predicted from theory. Attaining this maturity level makes them viable candidates for DoD system insertions. InP technology is estimated to be about 3 to 5 years behind GaAs in production maturity. This technology is one for which R&D is currently being conducted. It is expected to be challenged by WBG technology only at frequencies below 30 GHz. InP is expected to remain the technology of choice for the millimeter wave frequency range. High yield MMIC process development and reliability demonstrations will be required to reduce the risk to platform integrators for incorporating InP-based devices and integrated circuits in future E/M systems. Further device and circuit development is required to enable advanced millimeter wave communication systems and millimeter wave all-weather precision guided weapons.

Wide Bandgap materials, specifically SiC, GaN and their bandgap engineered derivatives, offer a 4-10 times increase in power density (W/cm^2) and power per device, compared to what can be achieved using GaAs or InP. In addition, they offer at least a 5x improvement in power-bandwidth product. Since the dielectric strength of these materials is decades higher than that of silicon, GaAs, and InP and the thermal conductivity of SiC is 4 times that of GaAs and InP, superior wide bandwidth, high power, highly linear, very efficient amplifiers are foreseeable. Also the potential for a paradigm shift to widespread use of class B push pull amplifiers is possible. This could offer the potential for simultaneous high efficiency and linearity, or higher operating temperatures (around 250 -C vs. 125 - C junction temperatures.) Figure 6.4 is a plot of frequency verses pulsed power output for a GaN HEMT amplifier showing the achievement of 25 watts of power output with PAE ranging from 15 to 28% across the band. Table 7.1 lists the major challenges to be overcome to enable implementation of GaN HEMT technology for military applications. The superior attributes of WBG devices potentially will lead to new generations of high performance solid-state RF systems, including the Navy AMRF-C, multifunction shipboard RF transmitter, Navy TBMD/volume search radar, AF/N standoff jammer arrays, Navy shipboard EW arrays, towed decoy upgrade/cost reduction, airborne radar upgrade/cost reduction, UAV/UCAV lightweight air cooled transmitters, and radiation tolerant space borne transmitters. Although WBG technology is progressing rapidly as demonstrated by rapidly improving device performance, it is about 10-15 years behind GaAs technology in maturity. Major challenges for WBG technology include a lack of adequate sources of suitable semi-insulating substrates, at an affordable price, and a current lack of equipment for achieving uniform doping over large diameter wafers. A basic understanding of the influence of material and processing variables on device performance and reliability is also needed. In particular, an understanding of performance drift and stability of GaN devices is essential before their insertion into DoD systems can be undertaken. Development of essential support technologies, unique for meeting the needs of WBG devices must also take place. These supporting technologies include packaging capable of handling very high levels of power dissipation and thermal management techniques compatible with the high thermal flux densities and higher voltage operation of these devices. Modeling and exploitation of the unique device physics inherent to this technology, such as piezoelectric effects at heterojunction layers is also required. With adequate investment, some advantages of this technology could be available for system insertion within a 5-10 year time frame.

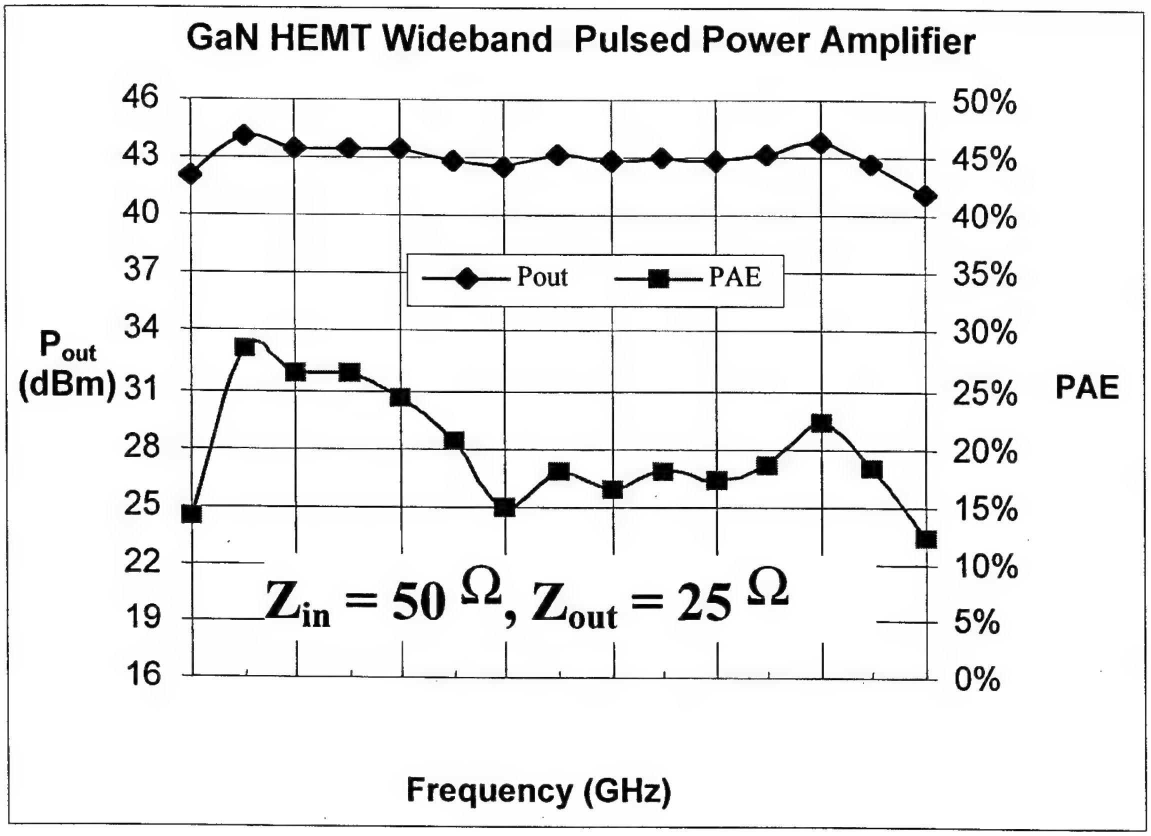

Figure 6.4. Recent GaN MMIC Results

Although there is significant commercial interest and investment in WBG semiconductors for the electro-optic applications such as light emitting diodes for displays, laser diodes for general purpose lighting and digital memory storage, and for other profitable applications such as gemstones for jewelry, there is currently little commercial interest in or significant investment directed toward maturing WBG devices for RF applications. To meet DoD needs for superior SS power amplifiers, a WBG development program, requiring an investment of approximately $250M over 5 years must be undertaken. Additional funding will be required to bring this technology to a level of maturity commensurate with the availability of highly qualified fabrication lines under SPC control. Such a program would be the equivalent of the MIMIC and MAFET programs of the 1990s for GaAs and InP technologies.

Subject	Issue	Power	Gain	Efficiency	Reliability	Cost
Physical Models	• Electron transport • Charge control	X	X	X		
Subrate Improvement	• Better surfaces • More insulating • Larger wafers • Lower cost		X		X	X
Layer Optimization	• Optimize thickness • Interfaces • AlGaN doping? • Passivation	X	X	X	X	
Contact Optimzation	• Lower resistance • Stability	X	X	X	X	
Wafer Thinning	• Microstrip circuit • Via etching • Thermal resistance	X	X	X	X	
Microwave Models	• Small signal • Noise • Large signal	X	X	X		
Monolithic Circuits - 1	• Transmission line • Compact layouts • Lumped elements	X	X	X		X
Monolithic Circuits - 2	• RF current limits • RF voltage limits • High efficiency modes			X	X	
Packaging	• Diamond heatsinks • High power bonds • Module integration	X			X	X

Table 6.1. Summary of GaN HEMT Development Challenges that impact performance parameters that are indicated by the checks.

Lightweight Flexible Array technology is required for the next generation of conformal array transmitters. Drastic (100x) reductions in transmitter weight and volume are required to enable future system concepts including micro-UAVs, space-based or aerostat-based air moving target sensors, multi-mode precision guided munitions, and man-portable communication and sensor systems. This revolutionary advancement requires moving past the traditional brick or tile based phased array structures, to large area flexible membrane structures. Novel hybrid technologies will be required to integrate multiple device types with all required matching and passive circuitry. Advanced modeling and simulation tools will be needed to allow design and simulation of large scale integrated RF assemblies.

A Tri-Service investment in infrastructure for GaAs, InP, SiC, GaN and derivative heterostructure power devices with a view toward realistic and timely insertions should be undertaken. This includes covering the full spectrum of tasks including materials and device development, design to circuit development, advanced packaging and module prototyping. It is necessary to investigate and evaluate the fundamental limits (noise, power, linearity, frequency response, reliability, etc.) of WBG semiconductor device technologies so that the exemplary performance projections for this technology can be confirmed and achieved.

6.1.2. SOLID-STATE TECHNOLOGY OPPORTUNITIES OVERVIEW

In overview, the Tri-Service investment in RF components for military applications is focused on (1) high power and high efficiency for transmitters, (2) spurious-free high dynamic range receivers, (3) solid-state device and IC technology, (4) stable frequency sources & clocks and (5) highly capable and versatile antennas. For the purposes of this document aimed at developing a strategy for investment balance between VE and SS technologies item (1) is of primary relevance, but item (3) is also an enabler of versatile active aperture solid-state systems with enhanced performance. The DoD SS portion of the high power & efficiency transmitters area is focused upon wide-band amplifiers for shipboard active arrays (e.g., AMRFS, DD-21) and UAV/UCAVs (e.g., Global Hawk), ultra-efficient amplifiers for space, high power amplifiers for search (e.g.,TPS-75) and the USMC MRRS, the Navy TBMD mission and volume search radar mission, millimeter wave amplifiers for missile seekers and precision munitions (e.g., BAT, TERM, Hellfire, Hammerhead, LOCAAS,) and communications. For system applications requiring an extremely low phase noise floor, heterojunction bipolar transistors (HBTs) are currently the best power amplifier choice. Stable local oscillators with phase noise characteristics equal to or better than the HBT amplifier must be used to accrue the full advantage of these very low phase noise devices. The FY 02 Tri-Service 6.2 investment in RF solid-state power and supporting materials technologies is about \$6.7M. The specific goals and projected funding levels for the funded programs are as follows:

Amplifier Type	Power Output	Frequency Range	Power Added Efficiency	Funding
Wideband (Using Wide Bandgap Technology)	Low Band: 250 Watts; High Band: 100 Watts	Low Microwave High Microwave		\$1.7M/year for 4 years
Ultra-efficient for Space	0.5 watt	X-band	70%	\$300K/year for 3 years
High Power for Radar	 40 watts	3 GHz (pulsed) 10 GHz	35% 35%	\$1.6M-\$2.1M/year for 3 years
Millimeter-Wave	10 watts 10 watts	30-40 GHz 94 GHz	25% 20%	\$2.6 M year for 1 year

Table 6.2. FY 02 Tri-Service 6.2 investment in RF solid-state power and supporting materials technologies

The greatest opportunity to advance microwave and millimeter wave SS power amplifier performance, at this time, is linked to the development of WBG semiconductors, devices, amplifiers, and integrated circuits, since components based on all other materials are at a considerably higher level of maturity. The availability of suitable, 3" or larger diameter wafers of SiC and GaN, with reproducible characteristics,

is of prime importance. The importance of satisfying this requirement is closely followed by the need to develop heterojunction device and circuit design.

The Tri-Service Road Map for RF solid-state power technology is provided in Appendix A.

6.2. *VACUUM ELECTRONICS TECHNOLOGY*

Vacuum electronic amplifiers are used in a wide variety of military and commercial applications, requiring high RF power at high frequency, as well as in scientific research areas such as high-energy particle accelerators and plasma heating for controlled thermonuclear fusion. The military has a critical reliance on vacuum electronic amplifiers for radar systems, electronic warfare systems, and for satellite communications (up-link, cross-link, and downlink) requiring high power, high efficiency, or high frequency. Currently there are close to 185,000 vacuum electronic amplifier sockets in over 270 military systems. The number is projected to increase to 190,000 (~3%) over the next 5 years and decrease slowly thereafter over the next 25 years if there are no new major VE based systems. The ability of a vacuum electronic amplifier to produce high power over wide bandwidths with high efficiency and at competitive cost and signal quality is a strong argument for an enduring role for this technology in military systems.

6.2.1. STATE OF TECHNOLOGY

Dramatic advances in vacuum device performance and capability have been achieved during the past decade. These advances can be credited to a combination of device innovation, enhanced understanding gained through improved physics-based modeling and design, the introduction of superior materials and sub-assembly components, and the development of advanced vacuum processing and construction techniques. The most familiar types of microwave vacuum electronic device, invented in the decade spanning the mid-1930s and 1940s, may be broadly classified as 'slow-wave' devices. This description as being 'slow-wave' emphasizes the fundamental requirement in these devices that the phase velocity of the electromagnetic wave on the interaction circuit must be approximately equal to the velocity of the electron stream if energy transfer between the beam and the wave is to occur. The electron velocity is less than the speed of light and hence the wave phase velocity must also be slower than the speed of light in free space. From the richness of device concepts investigated through the 1960s, the helix and coupled cavity traveling-wave tubes (TWTs), the klystron, magnetron, and crossed field amplifier (CFA) emerged as the primary products of today's technology.

The continuing vitality of this relatively mature segment of the technology is demonstrated by the recent development of a hybrid amplifier architecture, the microwave power module (MPM), that combines the best features of solid-state and vacuum technologies. This hybrid approach yields a cost-competitive amplifier that offers the power, efficiency, and bandwidth of a TWT with the reduced noise and functionality of a solid-state amplifier with either discrete or monolithic components.

Most significantly, this performance is obtained in a miniaturized package that can be a small fraction of the size of a comparable TWT amplifier (TWTA).

The MPM exemplifies the advantages accruing from a synergistic combination of evolutionary improvements in vacuum and solid-state technology. Noting the increased emphasis on a modular approach to RF system design, the MPM concept evolved from a belief that some form of vacuum device miniaturization could prove attractive for weight- or size-constrained systems requiring high efficiency. The MPM was envisaged as combining a low-gain vacuum power booster (a miniaturized PPM helix TWT) and a high-gain solid-state driver (using monolithic microwave integrated circuit (MMIC) technology) with an integrated power conditioner. By equalizing the distribution of gain in the power chain, the inherent efficiency of the TWT in the output stage augments the low-noise characteristics of the MMIC driver to produce a highly efficient amplifying module featuring wide-band, reduced noise performance.

The initial development of the MPM was highlighted by the demonstration of a 100-W transmit module operating from 6- to 18-GHz with an overall efficiency at band center of 40 %. The 50-dB module gain is equally balanced between the MMIC driver and the vacuum power booster (VPB). This fluid cooled version weighs 363 grams and has a volume of 120 cm^3. Relative to alternate technologies, this MPM offers a four-fold advantage in efficiency over GaAs MMIC alone, a greater than 20-dB improvement in noise figure over the TWT alone, and a more than ten-fold reduction in size relative to either a TWTA or GaAs SSPA. Taken overall, these improvements represent a dramatic breakthrough in microwave transmitter technology. The packaging, high overall efficiency and bandwidth capabilities of the MPM make it very useful for a wide range of commercial and military applications.

This continued growth of the PPM-focused TWT is not surprising given its dominance in the marketplace. As measured in terms of the basic parameters of information theory, the capabilities of the conventional TWT are impressive. The TWT is a key building block in the rapidly expanding telecommunication systems and retains a major role in satellite-based transmitters. With their increasing demand for bandwidth, military radar, electronic countermeasures, and communication data-links depend heavily on TWTs. In a package weighing less than a pound, the modern TWT provides average powers from tens of watt to hundreds of watt combined with a gain of ~ 60 dB and an instantaneous bandwidth of well over an octave. The basic distortion parameters can satisfy the most exacting requirements and the overall efficiency can be as high as 70 %. Moreover, the demonstrated lifetime for the wear-out of TWTs in the most demanding environment of space exceeds 18 years (> 150,000 hrs), which corresponds to an MTBF for random failure of ~ 10^7 hours.

The extension of vacuum device operation into the spectral range well beyond the microwave is a reasonable recent new trend. Beginning in the mid-1960s, two new classes of powerful 'fast-wave' device, the gyro-oscillator/amplifier and the free electron laser (FEL) have experienced ongoing development. In fast-wave devices, the phase velocity of the electromagnetic wave exceeds the speed of light in the interaction region.

Although the physical interaction mechanism is not the same, gyro-devices are technologically very similar to other microwave vacuum electronic devices. They differ primarily by their intrinsic need for magnetic field strengths typically available only from super-conducting magnets. In recent years, gyro-oscillators have produced output powers approaching a megawatt in the frequency range of 100 - 200 GHz with the pulse duration nearing a second. More importantly from the military perspective, an amplifier variant of this device type, the gyro-klystron, has been developed to provide 10 kW of average power at 94 GHz for radar application.

This evolution of source technology is captured in Figure 6.6, which shows device average power versus frequency at decade intervals extending from 1950 to the present. The rapid advances mentioned above are evident in this figure, as is the transition to new classes of device types that continue to extend the frontiers of performance in vacuum electronics. The convergence of lower frequency performance at the megawatt level and the power gap in the far IR respond to a lack of market interest, not the presence of any fundamental technical barrier. Although this presentation highlights the recent role of fast-wave devices in continuing the trend toward high power and frequency, it provides limited insight into the relative merits of a particular device type or its underlying physical interaction mechanism.

RF vacuum electronics technology advances continue in technical areas of power, power-bandwidth, efficiency, linearity, and noise reduction. Viewed using the $P_{av}f^2$ metric, a figure-of-merit allowing the comparison of vacuum electronics and solid-state devices, the history of RF vacuum electronics can be seen as successive waves of scientific innovation driven by technical opportunity coupled with market demand.

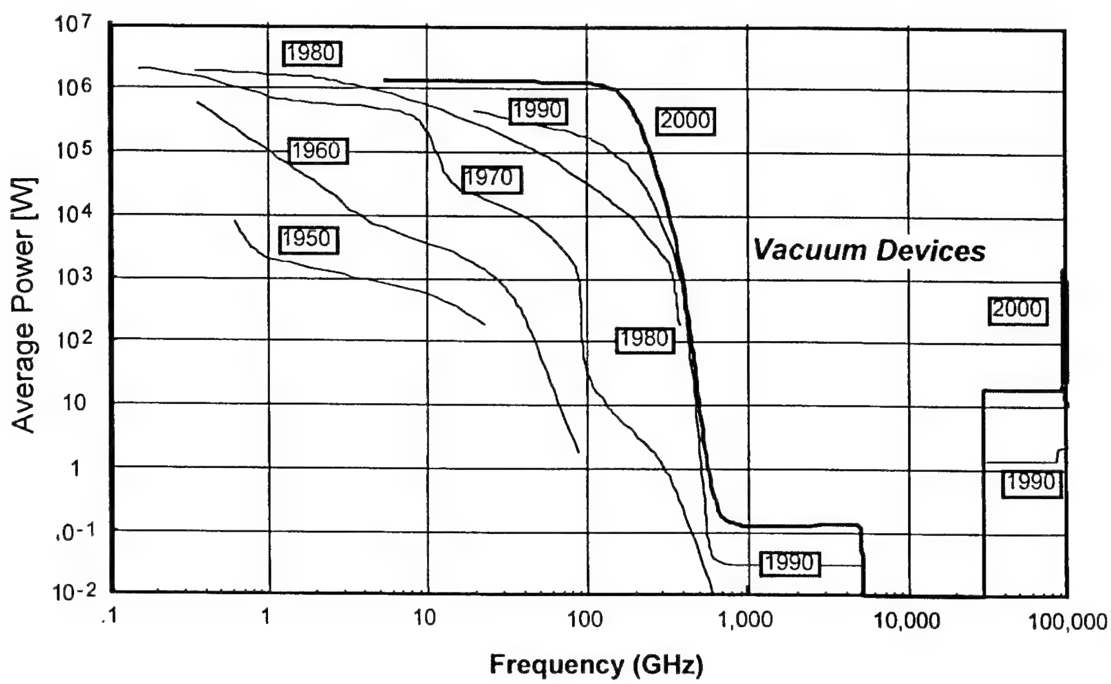

Figure 6.6. Vacuum Electronics Single-Device Performance (1950-2000)

First, the gridded tube was overtaken by the magnetron under the impetus of wartime demands.

The high-power linear-beam tubes, the klystron and the coupled cavity TWT, then move to the fore in response to accelerator and radar interests. Finally, the gyro-oscillator and the FEL surpass slow-wave devices in the mid-1970s. With these transitions, the envelope of vacuum device performance, as defined by the straight line in Figure 6.7, continues to grow at an approximate rate of doubling every two years, a rate sustained for the past 60 years.

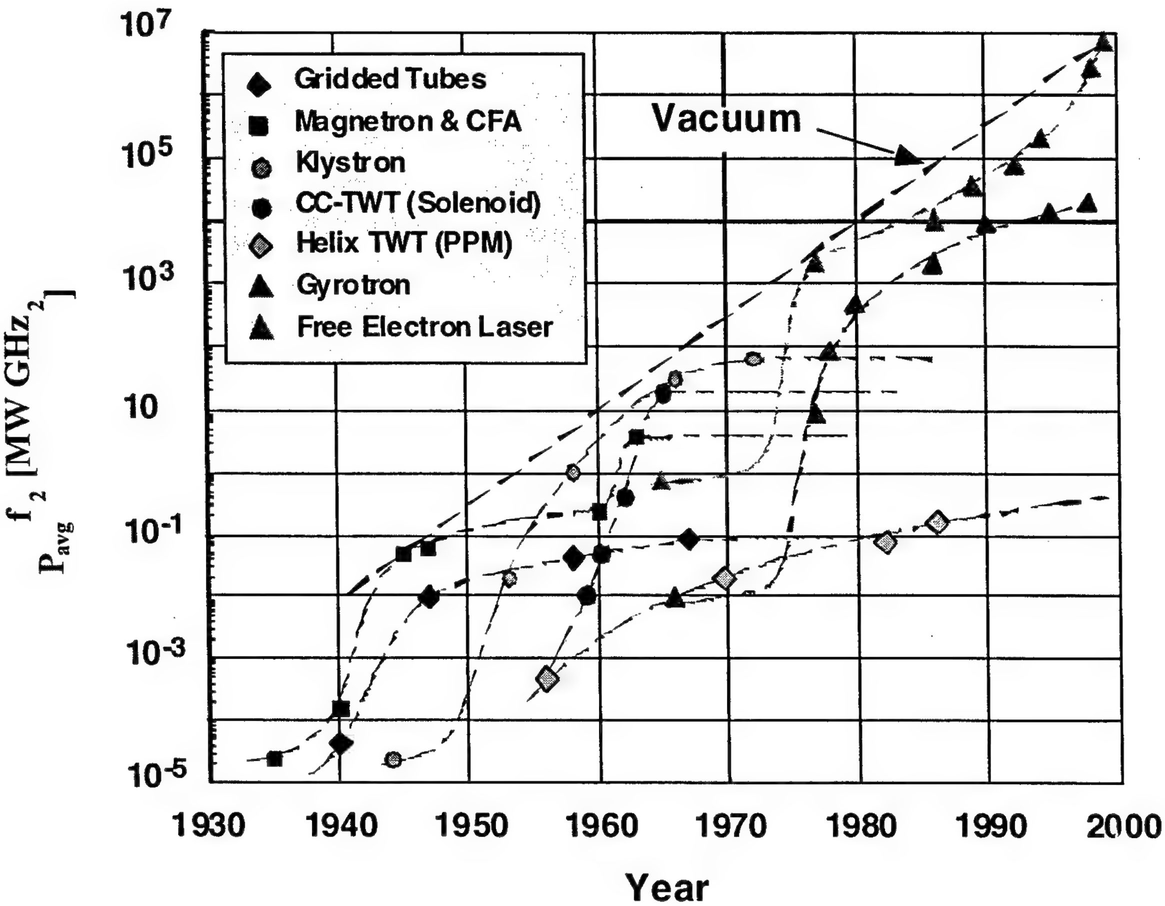

Fig. 6.7. Progression of device power density, $P_{av}f^2$, for major device types.

In general, the character of the research and developmental efforts associated with both fast- and slow-wave VE devices is commensurate with their relative state of maturity (as defined within the context of power density limits) and the market each serves. Fast-wave VE device efforts retain a strong research context but have become progressively more developmental in nature since the mid-1980s. Their areas of application (thermonuclear plasma heating; high-power, millimeter-wave radar; RF drivers for high-energy particle accelerators; and biological, chemical, and medical research in the sub-millimeter and IR) still require higher power performance at high

frequencies. Hence, market pull (non-military) and technological opportunity may coalesce to sustain the pursuit of high power at high frequency with fast-wave devices.

In contrast, the development of conventional microwave vacuum electronic devices is strongly driven by market demand. Most current military, commercial, and scientific applications do not simply require raw power, but rather some combination of adequate power output and more bandwidth, efficiency, and linearity or, possibly, lower noise and intermodulation distortion and, most recently, much higher phase fidelity. As new systems become more complex and expensive, their components must become smaller and lighter as well as more reliable. The 'horsepower' race that ended in the late 1960s has given way to an emphasis on the quality of the output. Although VE development may be evolutionary, its impact can be dramatic and important advances continue to be achieved within this broader view of performance.

6.2.2. Scientific and Technical Opportunities

Significant opportunities exist for advances in VE power amplifier performance achieved through improvements in the design and implementation of existing device concepts and by implementation of new device types and fabrication techniques.

6.2.2.1 *Modeling and Simulation*

Advances in modeling and simulation are having a profound effect on VE amplifier performance. A multi-dimensional, multi-frequency, design approach is required to accurately model the complex amplification process in VE amplifiers. Lack of adequate theoretical models that are capable of accurately predicting parasitic oscillations seriously prevents further advances in the performance of many VE devices. Accurate predictive capability for addressing both 2D and 3D stability related problems in helix and coupled-cavity TWTs and klystrons will allow further enhancement of the power handling ability of the devices as well as improvement of their linearity. Lack of theoretical models and algorithms that are capable of addressing the internal reflections in these amplifiers, can cause unacceptable gain and phase variations with frequency. This situation will prevent further improvement in VE performance that must be achieved if VE devices are to be used in high data rate communication applications. In addition, in order to model the amplification of wide-band digital signals there is a strong need for time-dependent analysis of the amplification process in all kinds of VE devices. Through high-fidelity computer modeling and optimization of the electron gun, circuit and depressed beam collectors, improvements in all aspects of device performance are possible. Integration of design tools based on the new models and algorithms will play a pivotal role in optimization of device performance parameters such as peak and average power output, efficiency, bandwidth and linearity. Continuing performance improvements will make possible new initiatives in VE device design with concomitant benefits for radar, communication, EW, and navigation systems performance.

Higher data-rates will be needed to support the information demands of Network Centric Warfare. To provide VE based transmitters meeting requirements for this

application area, the key scientific issues are: (1) developing accurate, physics-based, multi-frequency, large-signal models of linear beam and gyro-devices; (2) implementing these models with computational tools to facilitate the design of efficient, broadband, phase stable, linear amplifiers; and (3) developing optimization techniques capable of performing complex design trade-off analyses between the amplifier characteristics and their effect on overall communications link performance. Nonlinear amplifier models will be used to develop circuit designs that can be subsequently incorporated into communications link model. The effect of amplifier bandwidth, power, and distortion performance will be studied in the context of specific digital coding schemes and link performance requirements.

6.2.2.2 *MULTIPLE-BEAM AMPLIFIERS*

Multiple-beam amplifiers (MBAs) are a device technology with potential to provide the increased bandwidth, higher average power, and lower noise performance required for shipboard radars to keep pace with evolving anti-ship cruise missile (ASCM) and tactical ballistic missile (TBM) threats. MBAs use multiple axially-streaming electron beamlets that, at periodic intervals, are propagated through separate, parallel drift channels. These beamlets interact with electro-dynamic structures. The multiple beamlet configuration allows beam transmission at relatively low current densities with minimal space charge effects. This, in turn, enables the MBA to operate at a lower voltage and higher total beam perveance relative to that of a conventional klystron, These characteristics result in higher bandwidth and smaller size. The inherent 3D nature of the MBA results in the principal research challenges. These key research issues are: (1) developing 3D models of multiple-beam generation and transport; (2) incorporating these models into numerical design codes and validating the codes with experimental measurements; (3) development of efficient, broadband RF interaction circuits resulting in amplifiers with instantaneous bandwidths of up to 20%; and (4) development of efficient, multi-stage depressed collector designs for the multiple-beam geometry. Significant scientific and technical opportunities exist for exploitation of this type of device. If they are pursued, benefits to radar and communications systems will accrue.

6.2.2.3 *NEW MATERIALS*

New and improved materials have created opportunities for significant improvements in the performance of existing VE device types, in much the same way as semiconductor materials such as SiC and GaN are creating new performance opportunities for existing SSPA device types.

For example, the use of new and improved permanent magnetic materials, such as neodymium boron nitride, in conjunction with improved samarium cobalt materials can lead to an improved design of volumetrically efficient magnetic circuits. This would be made possible as a result of the high coercivity of rare-earth permanent magnets. The benefits of new magnetic materials have an immediate effect on VE device optimization. They also permit more stable device operation over a wider range of operating

environments (including space), reduced volume and weight, and reduced manufacturing costs.

Advances in chemical vapor deposition (CVD) of diamond films also has led to improved VE device performance. CVD diamond films possess thermal, mechanical, and electrical properties that are markedly different from those of BeO and APBN materials currently used in helix support rods. Key research issues and challenges that stem from these differences can be summarized as follows: (1) the possibility of new high power circuit and support rod designs that take advantage of the higher thermal conductivity of CVD diamond; (2) the realization of rod/circuit insertion techniques that are compatible with the mechanical properties of diamond; (3) development of cost-effective techniques to braze CVD diamond to the interaction circuit for further enhancement of thermal conduction; (4) metallization of CVD diamond for dispersion control; and (5) techniques for applying distributed loss onto diamond support rods for reflection suppression and oscillation control. Successful development of CVD diamond film technology may lead to the creation of a new class of VE devices that combine the peak/average output power performance of coupled-cavity TWTs and klystrons with the wide bandwidth achievable with helix TWTs.

The creation of new microwave-absorbing, ceramic-based composites, which exhibit dramatic but controllable variations in complex dielectric permittivity vs. frequency, would enable realization of new levels of performance. Specifically, materials exhibiting a $f^{0.85}$ to a $f^{1.5}$ power-law variation in dielectric constant, where f is the frequency, while maintaining a roughly constant loss tangent, would be exceptionally useful for the selective damping of frequency regimes prone to instabilities. Such materials, based on tailored microstructures exhibiting a spatial hierarchy with anomalous electron diffusion, would also make possible broadband dispersion control. When applied to coupled-cavity TWTs, these tailored-frequency response dielectrics should enable operation at higher spatial harmonics. This, in turn, would provide a 4-fold increase in average power capability at mm-wave frequencies. For fundamental space-harmonic coupled-cavity TWT's, a doubling of bandwidth capability is possible. Similarly, one would expect these new materials to increase the bandwidth capabilities of helix TWT's by a factor of 4. Finally, use of such materials should simultaneously provide a 50% increase in power and a 2.5 factor increase in bandwidth for gyro-TWTs operating at mm-wave frequencies.

Advanced cooling techniques based on porous-material heat exchange could also lead to greatly improved average power capabilities. For example, using porous-metal cooling wicks, power removal of 7-10 kW/cm^2 should be possible, compared to 1-2 kW/cm^2 levels achievable with standard technology. Additional improvements should be realizable using composite or non-metallic (e.g. ceramic or carbon-fiber) materials in the wick microstructure; this would also enhance reliability. Finally, two-phase coolant flow in composite wicks would provide an additional factor of 2 increase in power density. Such techniques promise to increase the power generation capabilities of mm-wave coupled-cavity TWTs and gyrodevices by factors of 2-3, while reducing the physical size and weight of the beam collectors. Passive, closed-loop, miniature heat-pipes, based on

this technology, should prove to be of great value for cooling MPM's, particularly those used in array configurations.

6.2.2.4 *ELECTROMAGNETIC STRUCTURE DESIGN*

Often, the average power available from VE devices is limited by the specific electromagnetic (EM) circuit design employed. Overmoded fast-wave interaction structures that are capable of handling high average powers while, at the same time, having sufficient loss at parasitic frequencies to stabilize amplifiers and suppress oscillation, will open up new opportunities for high-power, wide-band gyro-amplifiers. Advanced circuit designs that utilize external loading in a distributed manner along the circuit could yield substantially higher power mm-wave devices.

Photonic bandgap (PBG) EM structures have many useful properties which are beginning to find application in VE devices. These EM structures provide the designer with options for mode control that were heretofore unavailable. Opportunities exist for higher power operation of both slow-wave and fast-wave amplifiers, through the use of mode control PBG structures. Combined with the use of novel materials for mode control, these novel structures could yield power improvements of up to an order of magnitude for slow-wave devices such as klystrons and coupled-cavity TWTs.

6.2.2.5 *FABRICATION TECHNOLOGY*

The advent of high energy synchrotron machines, and the LIGA deep-lithography process collectively offer the possibility of fabricating high-performance millimeter-wave VE amplifiers at very low cost. Both MMW accelerator and VE amplifier structures have been fabricated using the LIGA process. This has led to improvements in device performance, packaging and cost. Further application of this new fabrication technique to the manufacture of MMW VE amplifiers could significantly lower device production costs.

6.2.2.6 *CATHODE TECHNOLOGY*

Research is required to provide robust, low-work-function coatings for Field Emitter Array Cathodes (FEAC's). Simultaneously, the feature size of their components (already at sub-micron dimensions) must be minimized and their lifetime and reliability must be increased. FEAC's offer the highly desirable characteristics of " instant ON/OFF", high pulse repetition frequency and modulation frequency, and cold emission at ultra-high current densities. Unlike existing technologies, their incorporation into RF VE devices, would allow for spatio-temporal modulation of the electron beams at the cathode surface. This, in turn, would result in reduced circuit length and improved overall efficiency. FEAC utilization would therefore benefit air-borne, decoy, and other systems where size, weight, bandwidth, and power consumption are issues, by, for example, improving the Vacuum Power Booster of the MPM.

Cathode materials fabricated from WBG semiconductors also are promising. However, additional research is required to determine, optimize, and control electron injection into and emission from low or negative work function material to achieve copious electron emission over a larger emission area. As electron sources, WBG emitters offer the advantages of instant ON/OFF performance, emission at low electric fields, and the absence of any requirement for the heater power needed by thermionic sources. Their utilization in RF VE devices would provide high current densities without compromising lifetime. This is because no dispensing of a low work function material would be required. They would also provide greater robustness in a vacuum electronic device environment. WBG cathode utilization, for example in the Vacuum Power Booster of the Microwave Power Module, would therefore benefit air-borne, decoy, and other systems where size, weight, lifetime, and power consumption are important considerations.

Robust, low-work-function scandate cathodes will provide high current densities (> 10 - 100 A/cm2) and uniform emission at low-temperature operation (~ 1000°C). By employing a pulsed-laser deposition technique, the cathode fabrication process is currently being optimized with respect to its film composition and the scandium replenishment capability. Scandate cathodes can provide the very high current densities needed for next-generation high-power millimeter wave devices, such as the multiple beam klystron. On the other hand, they can be operated at lower temperature and moderate emission density in order to reduce the power consumption and improve the lifetime of devices.

6.3. *S&T CHALLENGES AND OPPORTUNITIES*

In the sections that follow, S&T opportunities are presented in the context of ground, air, space, and sea needs that parallel the requirements and needs presented in Chapter 4.

6.3.1. GROUND

Most soldier man-pack electronics (communications and computers) must use as little energy as possible because of limited availability of power sources on the battlefield and weight considerations. Energy limitations and the need for portable, small, lightweight electronics dictate use of SS devices for these applications much as is true for commercial portable electronics. Munitions are required to be operational after being stored for up to 20 years in hostile environments. Hence, long shelf life is essential. In addition, munitions must be capable of being activated on very short notice. Gun launched munitions must withstand up to 18,000 G's of force. Ground radar for tactical forces must be mobile in-theater (6x6 vehicle or HMMWV); delivery to the theater (C-130 compatible) requires compact size and the ability to self-repair. Ground based EW is conducted from small fixed wing and rotary winged aircraft, which have limited prime power and weight carrying capabilities. Thus, these systems also require miniaturization and the ability to operate with high efficiency. Electronics for all of these applications must meet MIL-SPEC requirements including temperature ranges of -25-F to +125-F.

Ground based radar systems such as THAAD or its expected follow-on make use of larger array sizes, both to increase radiated power and to improve discrimination capability.

6.3.2. Air

Aircraft self-protection systems are increasingly making use of towed decoys that are based on VE devices but the cost of the decoy restricts more wide spread use. Future SS devices may be replacement candidates for VE if they can achieve comparable power over broad bandwidths with required high efficiency and at a reduced cost. High voltage on the towline, to reduce dissipative electrical power losses between decoy and platform, will continue to be used regardless of RF amplifier type in the decoy.

6.3.3. Space

Principal RF functions performed are surveillance (radar) and communication. Because of the stringent environmental considerations and need for operation over long periods of time, highly reliable VE devices and screened, high reliability, SS devices with high MTBF's, self diagnostics (Built in Test-BIT), and self healing ability must be used on these platforms. Radar apertures for earth observation are necessarily large. The requirement of large aperture size to meet mission requirements places serious demands upon missile lift capability. As a result, new emerging lightweight electronic packaging approaches such as the use of thin films capable of being spread over large areas is very attractive. In applications where communication with and between satellites is required, VE devices frequently constitute the most cost-effective choice of power amplifier. As is the case for SS amplifiers, their performance will require improvement in linearity and phase noise to allow effective use of new bandwidth-efficient signal formats such as m-ary QAM (quadrature amplitude modulation) and m-ary PSK (phase shift keying). SS amplifiers are viable candidates for use on future satellites with multiple beam transmission and dynamic foot printing although TWTs are used for this purpose now (e.g. NASA's Advanced Communications Technology Satellite (ACTS)) and will be competitive in the future.

6.3.4. Sea

The requirement for high efficiency operation over a wide temperature range combined with the need for multifunctional capability, has stimulated a high level of interest in newly emerging SS devices that hold promise for high efficiency, high performance operation and also offer the potential for cost savings and design flexibility to system designers.

Over the next 15 years, the Navy plans to introduce SS active arrays into the fleet to perform most current radar and EW functions and to augment the capabilities of these arrays so that they can perform additional functions. The high power required for some radar and EW missions imposes stringent cooling demands on systems. Achieving required isolation in a complex signal environment poses challenging linearity and

filtering problems. The Navy Radar Roadmap has identified wide bandgap (WBG) semiconductor RF-transmitters as an enabling approach to meeting these challenges. The follow-on Navy Radar Technology Roadmap (approved for release by ASN/RDA May, 2001), commissioned to recommend the necessary level of technology investment to support the Navy's radar development, identifies WBG technology as the only viable solution to meet its radar needs.

6.4. *RADAR RF POWER S&T CHALLENGES*

In the sections that follow, S&T opportunities are presented in the context of radar system requirements and needs as they are described in Chapter 4. An assessment of how well existing and envisioned capabilities of RF power amplifier technologies (**S&T Opportunities**) are expected to satisfy these requirements and needs are presented. Conclusions are drawn in a way that allows formulation of a balanced and appropriate investment strategy for both vacuum electronics and solid-state technologies.

Emerging Air Force UAV systems, such as PREDATOR and GLOBAL HAWK, represent platforms that require both VE and SS power amplifiers as well as sophisticated electronic antennas and automatic target recognition signal processing. Two dimensionally electronically scanned arrays are preferred because they afford exceptional operational flexibility through the ability to independently control the amplitude and phase of each element. Spatial combining of array elements allows high ERP to be achieved. SS amplifiers are used in several current radar systems – ground-based (THAAD), and air-based (F-22, JSF, F/A-18 E/F) and their use is planned in next-generation ship-based radars (MFR, VSR, TAMD). Concepts to develop highly multi-functional radars may impact the long term service life of legacy systems in the 2015-2025 time frame. These radars will most likely use SS amplifiers although VE approaches based on multi-beam amplifiers are also under study for some applications.

For the millimeter-wave tracking radar described in Chapter 4, the vacuum electronics gyro-amplifier is well suited to deliver the high power and wide bandwidth necessary for a W-band discrimination radar after appropriate R&D into specific device types such as the gyro-TWT.

Present ABM radars, such as the Army's GBR, illustrate that much remains to be done to further reduce the cost of SS T/R modules. For GBR, a production run of approximately 66,000 modules resulted in a final production cost of slightly less than $1000 per module. Much opportunity exists for further module cost reduction, using existing technology, through adoption of innovative, flexible and highly automated manufacturing and assembly approaches.

Clearly, the plethora of legacy systems to be upgraded and emerging radar systems expected to be fielded in the future represent both challenges and opportunities for RF electronic power amplifier transmitter development. Commercial spin-offs are expected to find service in FAA ground and air route surveillance systems as well as in harbor navigation and weather forecasting systems. The FAA is currently seeking a

cooperative agreement with the Navy related to the development of versatile multifunctional, SS powered radar. It is generally expected to look toward the Tri-Service DoD community for support in meeting its future radar needs. Commercial spin-ons are unlikely to be relevant since, in most cases, they will not meet military performance goals.

6.4.1. AIRBORNE RADAR

Numerous legacy airborne radar systems presently employ VE devices (e.g., AWACS APY-1). The most notable recent success story for VE is the Air Force's Predator UAV. It uses MPMs to perform the Ku-band SAR function as well as for its data link. For future GMTI radar on UAV platforms that operate in the Ka- through W-bands, extended interaction klystron amplifiers (EIKAs), as well as coupled-cavity TWTs establish the current performance baseline; improvements in their average power and bandwidth will be required. To provide better capabilities for detecting and tracking small, slow moving ground targets, increased phase stability will be required. UAV platforms are currently equipped with hybrid (solid-state and vacuum tube) microwave amplifiers. It is expected that, in the future, both improved VE technology and WBG solid-state amplifiers will be used to increase their operational versatility by making possible the realization of multifunctional apertures. To meet moderate power requirements at millimeter wave frequencies, InP-based SS devices and MMICs will most certainly be attractive candidate replacements for existing devices, especially in light of platform prime power limitations. To meet higher power requirements, MMW klystrons and coupled-cavity TWTs are likely to be required for future UAV millimeter wave systems. The three next-generation fighter aircraft, the JSF, the F-22 and F/A-18 E/F, will all employ X-band SS radar arrays. Although GaAs is the baseline technology for these systems, WBG device technologies could prove useful because of their ability to provide higher power and/or efficiency for future T/R module upgrades. WBG technology will not be ready for initial production of T/R modules for these platforms.

Solid-State	Vacuum Electronics
• To increase the mission capability of UAV platforms such PREDATOR and GLOBAL HAWK the use of multifunctional E/M active apertures is currently under consideration. SS active arrays are preferred because they lend themselves to very efficient spatial combining and afford exceptional operational flexibility through the ability to independently control the amplitude and phase of each element. • UAV platforms are currently equipped with microwave power module amplifiers. It is expected that, in the future, both improved VE technology and WBG solid-state amplifiers will be used to increase their operational versatility by making possible the realization of multifunctional apertures. • SS amplifiers are used in several current radar systems –air-based (F-22, JSF, F/A-18 E/F) • To meet moderate power requirements at millimeter wave frequencies, InP-based SS devices and MMICs will most certainly be attractive candidate replacements for existing devices, especially in light of platform prime power limitations • The three next-generation fighter aircraft, the JSF, the F-22 and F/A-18 E/F, will all employ X-band SS radar arrays	• Numerous legacy airborne radar systems presently employ VE devices (e.g., AWACS APY-1). • The Air Force's Predator UAV uses MPMs to perform the Ku-band SAR function as well as for its data link. • UAV platforms are currently equipped with hybrid (SS and VE) microwave amplifiers. It is expected that, in the future, both improved VE technology and WBG solid-state amplifiers will be used to increase their operational versatility by making possible the realization of multifunctional apertures. • To meet higher power requirements, MMW klystrons and coupled-cavity TWTs are certain to be required for selected future UAV systems.

Table 6.3. Summary of SS and VE Applications to Airborne Radars

6.4.2. SHIP-BASED RADAR

WBG semiconductor device technologies have been identified as key enablers for the TBDM radar due to the large increase in power-aperture-gain (PAG) required to perform this mission. To meet the PAG requirement within the limitations of ship architecture (i.e. aperture size) and cost, requires an element level power that markedly exceeds the capability of conventional (Si and GaAs) SS technology, but is feasible with

WBG technology. The potential of WBG devices to provide increased immunity to jamming, increased reliability, maintainability, and superior performance in the presence of clutter were considerations taken into account in selecting them for power amplifiers in planned follow-on radar systems. The rationale for their selection was based upon information collected during a Radar Technology Roadmap study, sponsored by the Assistant Secretary of the Navy, conducted at the end of calendar year 2000.

Although not on the present Navy Radar Roadmap, development of a multiple beam klystron (MBK) or, more generally, multiple beam amplifier (MBA) technology can provide needed improvements in average power, bandwidth, and noise performance for use in the AEGIS SPY-1B/D Midlife radar upgrade. Such development would also support NTW Block I, but not Block II. There is, however, no acquisition funding available or current plans for an MBA insertion, although some initial technology development planning for these amplifiers is underway. The SPQ-9B radar presently being readied for deployment in the Fleet uses a coupled-cavity TWT. Further performance improvements that can be achieved through the use of high-power MPM technology or MBKs include an increase in average power and reduction of noise. Such improvements are not currently included in the Navy Radar Roadmap because the SPQ-9B is scheduled to be replaced in the out years if other radar insertions meet their planned timelines.

Solid-State	Vacuum Electronics
• WBG semiconductor device technologies have been identified as key enablers for TBMD radar. To meet the PAG requirement within the limitations of ship architecture (i.e. aperture size) and cost, requires an element level power that markedly exceeds the capability of conventional (Si and GaAs) SS technology, but is feasible with WBG technology. • Increased immunity to jamming, increased reliability, maintainability, and the ability to perform better in the presence of clutter were considerations taken into account in creating the plan to implement AEGIS-like follow on radars with WBG semiconductor technology	• Although not on the present Navy Radar Roadmap, development of a multiple beam klystron (MBK) or, more generally, multiple beam amplifier (MBA) technology can provide needed improvements in average power, bandwidth, and noise performance for use in the AEGIS SPY-1B/D midlife radar upgrade. Such development would also support NTW Block I, but not Block II. • The SPQ-9B radar presently being readied for deployment in the Fleet uses a coupled-cavity TWT. Enhanced power and noise performance is possible with high power MPMs or MBKs.

Table 6.4. Summary of SS and VE Applications to Ship-Based Radars

6.4.3. GROUND-BASED FIXED AND MOBILE RADAR

The near- and mid-term use of VE technology for radar systems described in Chapter 4.2.3 is exemplified by the Army's choice, within the past year, of TWTs as the amplifier technology for the S-band AN/TPQ-47 radar. The new MMR will combine artillery and mortar surveillance functions, using power levels consistent with those achievable with a TWT corporate-fed phased array capability. A WBG solid-state approach had been seriously considered for the AN/TPQ-47, but the technology was not mature enough for insertion on the required time line.

To meet cost of ownership requirements described in Chapter 4.2.4, TWT transmitters are the most cost-effective choice for providing required RF characteristics including the necessary prime power and a cooling power solution that is consistent with light system weight. The USMC Multi Role Radar System, in contrast, contemplates the use of an active aperture, all SS radar. As the US Army increasingly becomes a lighter, more mobile force, it is anticipated that it too will integrate multiple radar functions.

Solid-State	Vacuum Electronics
• The USMC Multi Role Radar System, contemplates the use of an active aperture, all SS radar	• Within the past year, the Army has chosen TWTs as the amplifier technology for the S-band AN/TPQ-47 radar. A WBG solid-state approach had been considered but it was not mature enough for insertion on the required time line. • The Army's new Multi-Role Radar (MMR) will combine artillery and mortar surveillance functions, using power levels consistent with those achievable with a TWT corporate-fed phased array capability. • The Army believes that TWT transmitters are the most cost-effective choice for providing required RF characteristics including necessary prime power and cooling power consistent with light system weight.

Table 6.5. Summary of SS and VE Applications to Ground-based Fixed and Mobile Radars

6.4.4. GROUND-BASED FIXED INSTRUMENTATION AND SURVEILLANCE RADAR

Satisfying the Air Force's Space HUSIR requirement described in Chapter 4.2.4 may require use of wideband gyro-TWT vacuum electronics technology to meet power and bandwidth specifications.

There are several VE related approaches to the development of the imaging radar system described in Chapter 4.2.4 for upgrading the Kwajalein Missile Range radar. In Ka-band, the desired output power is 100 kW peak, 20% duty factor, with 4 GHz instantaneous bandwidth. Gyro-amplifier technology is the most likely approach to meeting these requirements.

No RF amplifier technology presently available can provide the 1 kW (average) and 5 kW (peak) power required for the Haystack radar upgrade over the 92 to 100 GHz band. One approach proposed to meet this requirement, is the development of a W-band TE_{01}-mode gyro-TWT. Its implementation will require developing novel circuits that are compatible with very high power loading. This loading characteristic is necessary to implement the distributed loss essential to assure overall amplifier stability. Other critical development items for this gyro-TWT include the input coupler and output window. Other VE approaches, such as use of a combination of several coupled cavity TWTs, may also be applicable to the Haystack radar upgrade and could be considered for satisfying the needs of this one-of-a-kind application.

Solid-State	Vacuum Electronics
	• The Air Force's Space HUSIR radar requires amplifier technology capable of operating at a peak power level of >5 kW, 20% duty factor, and an 8 GHz instantaneous bandwidth. Satisfying this requirement may require use of wideband gyro-TWT vacuum electronics technology. • Measurements of characteristics of ballistic missile intercepts at the Kwajalein Missile Range (KMR) rely on use of the millimeter-wave radar system that is part of the Kiernan Reentry Measurement System (KREMS) on Kwajalein atoll. There are several VE related approaches to the development of such an imaging radar. Upgrading the Kwajalein Missile Range radar is needed for TBMD and National Missile Defense (NMD) evaluation. In Ka-band, the desired output power is 100 kW peak, 20% duty factor, with 4 GHz instantaneous bandwidth. • The US Space Command is currently engaged in discussions with MIT Lincoln Laboratory regarding an upgrade to the Haystack radar. The proposed upgrade calls for frequency of operation to be increased to W-band No SS approach can meet the requirements of this radar system. One approach proposed to meet them is the development of a W-band TE_{01}-mode gyro-TWT. Another possibility is the use of several coupled-cavity TWTs.

Table 6.6. Summary of SS and VE Applications to Ground-based Fixed Instrumentation and Surveillance Radars

6.4.5. MISSILE SEEKERS

Small wafer level phased array antennas, implemented with currently available solid-state technologies (GaAs or InP), would solve gimbal reliability problems described in Chapter 4.2.5. To achieve smaller size munitions with higher performance than current SADARM and BAT systems require even higher frequency operation to achieve acceptable aperture gain and necessitate development of higher power SS device technologies at frequencies above 94 GHz.

Solid-State	Vacuum Electronics
• Missile seekers are decreasing in size. Use of SS is attractive. • Small wafer level phased array antennas, implemented with currently available solid-state technologies (GaAs or InP), would solve gimbal reliability problems prevalent in current missile seekers. • Higher power SS device technologies are needed at frequencies above 94 GHz.	• Missile seeker development at millimeter wavelengths is under consideration. Improved EIAs, CC-TWT's and MMPMs needed.

Table 6.7. Summary of SS and VE Applications to Missile Seekers

6.5. *ELECTRONIC WARFARE S&T CHALLENGES*

In the sections that follow, S&T opportunities are presented in the context of electronic warfare system requirements and needs as they are described in Chapter 4. An assessment of how well existing and envisioned capabilities of RF power amplifier technologies (**S&T Opportunities**) are expected to satisfy these requirements and needs are presented. Conclusions are drawn in a way that allows formulation of a balanced and appropriate investment strategy for both vacuum electronics and solid-state technologies.

Signal-to-jam (S/J) ratio, or power-on-target, are of fundamental importance for EW systems needs as described in Chapter 4.3. Powers of up to 200 watts (CW) and 2-5 kW (pulsed) over multi-octave bandwidths through millimeter-wave frequencies are essential for use in EW systems, almost all of which current employ 1-D (fan-shaped) E/M beams. VE power amplifiers are the only devices that can provide the required high power, wide bandwidth, and high efficiency. To operate effectively against agile–agile radars, future EW systems will likely use two-dimensional electronically steered beams. Eventually, EW systems could benefit from the projected performance of new SS device technologies, such as WBG semiconductors, particularly in systems that make use of active aperture, 2-D beam concepts. However, development of WBG technology is presently at the R&D stage. Newer electronic attack EW systems such as AIEWS

Increment II will use planar active aperture arrays that to accomplish their functions will be powered by SS technology.

For the Navy's planned advanced NULKA shipboard decoy system consideration is being given to the use of an active aperture, 2-D E/M beam concept to improve operating lifetime of a legacy VE system whose E/M beam is pointed by rocket engine vectoring of the entire platform. In future multifunctional system implementations incorporating EW, the concept of using a 2-D pencil beam with increased RF energy density may be possible. This will increase the likelihood of being able to use SS amplifiers as replacements for VE. As conventional narrow band noise jamming will be far less effective against future generations of wide band radars that employ advanced modulation technologies will require either improved-performance VE or wide bandgap semiconductor RF technologies.

Air Force towed decoys systems use VE RF amplifiers. Future towed RF decoys will continue to use high voltage on the towline to mitigate against dissipative loss. The choice of SS or VE amplifiers for emerging towed decoy systems will be dictated by required performance and amplifier availability, and affordability.

At present, the traveling wave tube (TWT) is the device of choice for wideband jamming in the 100 watt (CW) and 1-2 kW (pulsed) range. Within the last decade, however, microwave power modules (MPMs) and millimeter wave power modules (MMPMs) have become attractive alternatives; their performance has extended the power-bandwidth capability of RF transmitters and their configuration supports the advantages of modular design and flexibility. These MPMs are capable of meeting the 100-watt (CW) power requirement listed above and have instantaneous bandwidths from 2- to 6-GHz and 6- to 18 GHz. At higher frequencies, 50- to 100-watt (CW) MMPMs will be required with instantaneous bandwidths of 18- to 40-GHz and 30- to 40-GHz, the higher power being associated with the latter bandwidth. The MPM and MMPM are important for their compactness, lightweight, and high DC-to-RF efficiency. For example, their small size and weight permit them to be mounted near an antenna, thus reducing transmission losses; their power-bandwidth capability and efficiency make them uniquely suited for use in towed decoys and UAVs. In the future, MPMs and MMPMs will be used for self-protection, escort, standoff, and stand-in jamming, as well as on towed decoys. The mid-term extension to a 2- to 18-GHz, greater than 100-watt (CW) unit will provide logistical simplicity, as well as weight, size, and cost savings. Long-term EW transmitter needs include transmitters suitable for active array applications on constrained size and weight platforms. Now that MPM and MMPM performance has been demonstrated, programs to improve reliability and producibility for lower cost of ownership are critical. In the future, WBG technology will provide healthy competition for VE based MPM's as it reaches maturity and its full capabilities and limitations become known.

The Army's SIRFC requires wideband amplifiers for both the microwave and millimeter wave frequency domains. SIRFC includes both RF and EO jammers, for which MPMs and MMPMs represent the near- and mid-term choice for RF amplification

because of their small size, multi-octave bandwidth frequency coverage, high power, and overall high efficiency. Although substantial work and rapid progress has been made on MPMs, they were not ready in time for use in many of the mid-90's EMD jammer program starts. Work needs to continue on these MPMs so that they can be used for equipment upgrades and possibly as replacements during spares purchases for jammer programs.

Solid-State	Vacuum Electronics
• The Navy's planned advanced NULKA shipboard decoy system is expected to be more energy-efficient than most current EW systems. In future multifunctional system implementations incorporating EW, the concept of using a 2-D pencil beam with increased RF energy density may be possible. If so, it will result in lowered RF amplifier power requirements per element. This will greatly increase the likelihood of being able to use SS amplifiers as replacements for VE. • Future towed RF decoys will continue to use high voltage on the towline to mitigate against dissipative loss. The choice of SS or VE amplifiers for emerging towed decoy systems will be dictated by required performance and amplifier availability, and affordability. • Provided that scan angle, linearity, and power-per-multiple-targets can be achieved, EW systems will increasingly exploit active aperture antenna designs. Advances in WBG technology will provide healthy competition for VE based MPM's as it reaches maturity and its full capabilities and limitations become known. • To operate effectively against agile–agile radars, future EW systems will likely use two-dimensional electronically steered beams.	• Most current EW systems employ 1-D (fan-shaped) electromagnetic beams. Although they are beam energy inefficient, they are cost effective as single function systems. For all potential platforms (e.g., the F-derivatives, JSF, UAVs) that use 1-D fan-shaped E/M beams, the use of VE power amplifiers provides almost the only viable technology, because it is the only technology that can provide the required high power, wide bandwidth, and high efficiency. • The Army's basic aircraft jamming systems, AN/ALQ-136 and AN/ALQ-162, are being upgraded as part of the SIRFC program. SIRFC requires wideband amplifiers for both the microwave and millimeter wave frequency domains. Current systems use VE RF amplifiers. SIRFC includes both RF and EO jammers, for which MPMs and MMPMs represent the near- and mid-term future choice for RF amplification because of their small size, multi-octave bandwidth frequency coverage, high power, and overall high efficiency • At present, the TWT is the device of choice for wideband jamming in the 100 watt (CW) and 1-2 kW (pulsed) range. Within the last decade, however, microwave power modules (MPMs) and millimeter wave power modules (MMPMs) have become attractive alternatives.

Table 6.8. Summary of SS and VE Applications to Electronic Warfare Systems

6.5.1. Airborne Self Protect and Support Jamming

The modular transmitter concept should replace older, bulkier, less-efficient, low- and high-band solutions employing high-voltage TWTAs. This will simplify RMA (Reliability / Maintainability/Availability) needs. Multifunctional RF systems are expected to be capable of increasing operational versatility of UAVs and UCAVs,. These systems will undoubtedly require advances in power amplifier technology, both VE and SS.

6.5.1.1 *2 to 18 GHz*

MPMs are building blocks, capable of providing 100s of watts of CW power, coupled with respectable prime power efficiency. However, their signal fidelity must be enhanced, and their amplitude/gain/ power and phase tracking characteristics must be appropriate for supporting advanced array architectures. Spatial constraints of AIEWS will constitute a challenge for VE technology. System linearity must be enhanced, output power increased, and high prime power efficiency achieved, all within a very small package. Production techniques must be developed to achieve required amplitude / gain / power and phase tracking. Far-term objectives for the Ultra Wideband MPM operating between 2 and 18 GHz include 300 watts (CW), 46% prime power efficiency, -10 dBc 2nd harmonic power, and -160 dBc/Hz @ 10 kHz offset in a 35 cu. in. package and costing $10/watt.

6.5.1.2 *18 to 40 GHz*

The MMPM also provides building-block power of 100s of watts (CW) coupled with acceptable prime power efficiency. MMPMs must have suitable amplitude / gain / power and phase tracking characteristics for supporting advanced array architectures. The development of production techniques to repeatably produce MMPMs meeting the amplitude / gain / power / phase tracking requirements is particularly important at higher frequencies. Far-term objectives for the (18 – 40 GHz) MMPM are 200 watts (CW), 38% prime power efficiency, -20 dBc 2nd harmonic power, ±10 deg phase tracking, ± 1 dB gain tracking, ±1 dB power tracking in a 40 cu. in. package at a cost of $30/watt. The need for greater phase stability and linearity for MPMs and MMPMs will be addressed by using advanced physics-based models and simulation techniques.

Solid-State	Vacuum Electronics
• The most advanced new EW system is the AIEWS. It uses a planar array. Spatial constraints of AIEWS will constitute an extreme burden for VE technology. System linearity must be enhanced, output power increased, and high prime power efficiency achieved, all within a very small package. • If millimeter wave EW system architectures migrate to active aperture planar arrays as is the case for the latest microwave systems, power requirements will be considerably reduced making SS amplifiers attractive power amplifier candidates.	• For systems using 1-D array architecture, Ultra Wideband MPMs are the leading candidates as power amplifiers. Far-term objectives for these MPMs (operating between 2 and 18 GHz) are 300 watts (CW), 46% prime power efficiency, -10 dBc 2nd harmonic power, -160 dBc/Hz @ 10 kHz offset, ±2 deg phase tracking, ± 1 dB gain tracking, ± 0.50 dB power tracking in a 35 cu. in. package and costing $10/watt. • For millimeter-wave systems, the MMPM provides building-block power of 100s of watts (CW) coupled with acceptable prime power efficiency.

Table 6.9. Summary of SS and VE Applications to Airborne Self-Protect and Support Jamming

6.5.2. SHIP-BORNE AND GROUND-BASED SELF PROTECTION

Scalable (i.e. modular) transmitter architectures will support a wide variety of platforms, including both manned and unmanned vehicles, that require protection. In addition to higher ERP, transmitters must provide a level of linearity that is suitable for arrays supporting polarization techniques and independent beam steering.

6.5.2.1 *2 TO 18 GHZ*

For 1-D arrays, the MPM as described in section 5.3.1.1 above represents the most appropriate power amplifier choice. The Navy is funding a study to determine whether an advanced NULKA stand-off EW deception missile can be configured as a SS active aperture array with beam pointing/steering capability, instead of relying on rocket engine power to point the missile and its fixed antenna as the present NULKA system does.

6.5.2.2 *18 TO 40-GHZ*

The comments about MMPM's in section 5.3.1.2 apply. If ship-borne and self-protection systems, operating at millimeter wave frequencies are incorporated into multifunctional systems or become 2-D systems, then WBG solid-state active aperture arrays will predominate, since VE devices are currently not envisioned to be small enough to fit into such 2-D active aperture arrays. Affordability issues will ultimately determine if 2-D arrays become viable.

Solid -State	Vacuum Electronics
• In the future, the Navy's advanced NULKA stand-off EW deception missile may be configured as a SS active aperture array with beam pointing/steering capability. • If ship-borne and self-protection systems, operating at millimeter wave frequencies are incorporated into multifunctional systems or become 2-D systems, then WBG SS active aperture arrays may be most effective since VE devices are currently not envisioned to be small enough to fit into such 2-D active aperture arrays at higher microwave frequencies. Affordability issues will ultimately determine if 2-D arrays become viable.	• For 1-D arrays, the MPM represents the most appropriate power amplifier choice. • For millimeter-wave systems, the MMPM provides building-block power of 100s of watts (CW) coupled with acceptable prime power efficiency.

Table 6.10. Summary of SS and VE Applications to Ship-borne and Ground-Based Self Protection

6.6. *COMMUNICATIONS S&T CHALLENGES*

In the sections that follow, S&T opportunities are presented in the context of communications system requirements and needs as they are described in Chapter 4. An assessment of how well existing and envisioned capabilities of RF power amplifier technologies (**S&T Opportunities**) are expected to satisfy these requirements and needs are presented. Conclusions are drawn in a way that allows formulation of a balanced and appropriate investment strategy for both vacuum electronics and solid-state technologies.

The diversity of platform and performance requirements necessitates the development of both improved VE and SS amplifier technologies. Relevant SS technologies include GaAs, InP, and the promising WBG semiconductor technologies, SiC and GaN. Promising VE technologies include helix and coupled-cavity TWTs and microwave power modules (MPMs), for both microwave and millimeter-wave frequency operation.

At present, for frequencies above 20 GHz, TWTs have been space qualified at 20 GHz (120W, helix), 32 GHz (10 W, helix), and 60 GHz (50 W, coupled-cavity). TWTs for terrestrial links are in low rate production at 45 GHz (120W, helix) and coupled-cavity TWTs have been demonstrated with power outputs of up to 1 kW at 30 GHz. New broadcast systems will require substantial increases in operating power, linearity, and efficiency without suffering a reduction of reliability. New materials, micro-fabrication manufacturing technology, and 3D CAD design techniques are all expected to contribute to the achievement of improved performance. Linearity and efficiency are inextricably

connected to improved TWT performance; the use of improved multi-stage depressed collectors can provide a substantial improvement in linearity with relatively high efficiency. Versatile new systems employing beam pointing and footprint diversity may employ lower power solid-state devices with their inherently superior phase stability. Low power solid-state amplifiers having the best phase stability and linearity usually use heterojunction bipolar transistors.

For all communication systems, wide analog bandwidths, much improved linearity and phase stability, and high average power are required in order to support increasingly high transmission data rates (HDR) achieved with complex m-ary signaling formats. Helix and coupled-cavity TWTs, as well as millimeter-wave klystrons are key technologies for single function system architectures. Spatial limitations dictate that shipboard applications will increasingly require shared apertures; for these applications, SS technology is expected to be employed.

Extremely efficient SS power amplifiers and MMIC's operating at low voltages with high linearity, power recovery circuits and low intermodulation distortion will be required to meet 21st century battle-space requirements for terrestrial communication systems operate at frequencies between 30MHz and several GHz.

The conventional TWT Amplifier (TWTA), used successfully in current-generation commercial broad footprint satellite transponders, displays 15-year service life, radiation hardness, and outstanding efficiency. To meet HDR requirements, however, even greater power (within the limited bandwidth available) must be provided with much better linearity, reduced gain ripple and reduced phase ripple. Alternative approaches to increased HDR include much improved phase stability. In traditionally designed TWTs, linearity is achieved at the expense of power, i.e., power is reduced from the saturated level to levels available in the linear regime of operation. However, advanced simulations indicate that it may be possible to design a new class of TWT that provides power without the necessity for trading off linearity. It is estimated that this new class of TWT will enjoy an improvement of between 3 and 6 dB of power output. This, in turn, would afford new communications capabilities for military users.

The power amplifier technology employed for multiple simultaneous footprint beam pointing and beam shaping capability will most likely be SS. However, a combination of advanced VE technology and solid-state WBG technology may be used together. The choice will ultimately depend on system factors such as range, antenna gain, data rate, and the required link margin against weather and jamming.

6.6.1. Ground Segment

The U. S. Army's Secure Mobile Anti-Jam Reliable Tactical Terminal (SMART-T) presently uses a SS pHEMT transmitter that provides only 25 to 30 watts of power and consequently experiences difficulties in link closure under adverse weather conditions. Present and future ground-segment terminals for SMART-T and lower data rate systems can use improved TWTs and MPMs to meet tight space and volume constraints while

improving on uplink power. The MMPM technology base developed for the 18- to 40-GHz wideband applications has been tailored to provide a Phase I power of 40- to 50-watts (CW) with a 25% DC-to-RF efficiency within a 35 cu in package that weighs about 4 lbs. Even higher powers are available using a conventional TWT. It is capable of providing 120 Watts (CW) across the band. However, packaging and cost issues remain to be resolved, since the TWT amplifier configuration requires voltages on the order of 13.5 kV, twice that used by MMPMs. As data rates and the need for lower bit-error-rates increase, additional VE upgrades will be required to meet the single function design architecture and system operating parameters described in Section 4.4.1. Lower power requirements for active aperture arrays that employ multiple simultaneous signals may be met with WBG semiconductor technology at frequencies up to 25 GHz during the 2010 timeframe and at higher frequencies in the longer term.

Solid-State	Vacuum Electronics
• The U. S. Army's Secure Mobile Anti-Jam Reliable Tactical Terminal (SMART-T) is a MILSTAR-frequency (43.5- to 45.5 GHz) uplink. The goal of achieving 100% link availability with a 10 Mbps data rate presently requires a transmitter power of 75 to 80 watts. The transmitter package volume is limited. The presently used SS pHEMT transmitter provides only 25 to 30 watts of power and consequently experiences difficulties in link closure under adverse weather conditions • Power requirements for active aperture arrays that employ multiple simultaneous signals are much lower. These requirements are expected to be met with WBG semiconductor technology at frequencies up to 25 GHz during the 2010 timeframe and at higher frequencies in the longer term.	• Present and future ground-segment terminals for SMART-T and lower data rate systems can use improved TWTs and MPMs to meet tight space and volume constraints while improving on uplink power. • MMPM technology base developed for the 18- to 40-GHz wideband applications has been tailored to provide a Phase I power of 40- to 50-watts (CW) with a 25% DC-to-RF efficiency within a 35 cu in package that weighs about 4 lbs. • Even higher powers are available using a conventional TWT. It is capable of providing 120 Watts (CW) across the band. However, packaging issues remain to be resolved, since the TWT amplifier configuration requires voltages on the order of 13.5 kV, twice that used by MMPMs • As data rates and the need for lower bit-error-rates increase, additional VE upgrades will be required to meet the single function design architecture and system operating parameters

Table 6.11. Summary of SS and VE Applications to Ground Based Portion of Satellite Communication Systems

6.6.2. Space Segment

The TWT is the dominant technology used today in most satellite transponders, due to its efficiency (~70%), demonstrated reliability (56 failures per billion hours of operation), and high power capability. Virtually all amplifiers flying on commercial spacecraft today are TWTs; this situation is likely to continue until more versatile multiple beam, controlled footprint systems are fielded or until superior higher power solid-state (WBG) amplifiers are available. The continued development of TWT technology with renewed emphasis on improved linearity, lowered phase noise floor, improved efficiency, and increased power capability in the conventional SATCOM bands is needed. For revolutionary micro-satellite applications requiring ultra-compact high power transmitters, the MPM and MMPM should be developed in order to enable the next generation of communication systems for space based applications. These MPMs and MMPMs will most probably incorporate WBG semiconductor driver amplifier stages.

Solid-State	Vacuum Electronics
• MPMs and MMPMs for the next generation of communication systems for space-based use will most probably incorporate WBG semiconductor driver amplifier stages. • Maturation of higher power solid-state WBG amplifiers should create opportunities for insertion in future satellites.	• The TWT is the dominant technology used today in most satellite transponders, due to its efficiency (~70%), demonstrated reliability (56 failures per billion hours of operation), and high power capability. Virtually all amplifiers flying on commercial spacecraft today are TWTs; this situation is likely to continue until more versatile multiple beam, controlled footprint systems are fielded or superior higher power solid-state amplifiers are developed. • The continued development of TWT technology with renewed emphasis on improved linearity, lowered phase noise floor, improved efficiency, and increased power capability in the conventional SATCOM bands is needed. • For revolutionary micro-satellite applications requiring ultra-compact high power transmitters, the MPM and MMPM should be developed in order to enable the next generation of communication systems for space based applications

Table 6.12 Summary of SS and VE Applications to Space-Based Portion of Satellite Communication Systems

6.6.3. Cross-Links & Relay Nodes

Cross links for satellite constellations, operating in the 50 – 65 GHz frequency range, must also support higher data rates described in Section 4.4. Both helix and coupled-cavity TWTs, either stand-alone or configured as MPMs, are well suited to meeting the required near term power output of 75W * with 55% power added efficiency that is required and the far term requirement for 500 W with 50% power added efficiency. * See Appendix C

Operating frequencies even higher than V-band have been envisioned for some future communication networks such as UAV-based relay nodes. If the communication relay by UAV is to simultaneously perform other functions, a multifunctional active aperture array may be a better choice; it will most likely employ SS technology. For future systems, the use of high-order digital modulation will require optimization of the efficiency and phase stability of transmitters within tight linearity constraints that will require improvements in both SS and VE technologies.

Solid-State	Vacuum Electronics
• If UAVs are to simultaneously perform a multiplicity of functions, a multifunctional active aperture array may be a better choice than the current approach; it will most likely employ SS technology.	• Cross-links of satellite constellations, operating in the 50 – 65 GHz frequency range, must support higher data rates. In the near term, a power output of 75W with 55% power added efficiency is required. In the far term, 500 W with 50% power added efficiency will be required. New highly efficient, high power laser-based systems may provide significant competition to RF. • Communication relay by UAV is to be an increasingly important mission. Both helix and coupled-cavity TWTs, either stand-alone or configured as MPMs, are well suited to meeting this future need

Table 5.10. Summary of SS and VE Applications to Cross-Link & Relay Node Portion of Satellite Communication Systems

6.7. *MULTIFUNCTIONAL ELECTROMAGNETIC SYSTEMS S&T CHALLENGES*

In the sections that follow, S&T opportunities are presented in the context of multifunctional electromagnetic system requirements and needs as they are described in Chapter 4. An assessment of how well existing and envisioned capabilities of RF power amplifier technologies (**S&T Opportunities**) are expected to satisfy these requirements and needs are presented. Conclusions are drawn in a way that allows formulation of a balanced and appropriate investment strategy for both vacuum electronics and solid-state technologies.

Multifunctional electromagnetic systems combine into one aperture the functions that would otherwise require several apertures and their system needs are described in detail in Section 4.5.

The amplifier choices for a multifunctional system active array system with a separate RF amplifier directly behind each radiating element are SS amplifiers (SSAs), VE devices, or microwave power modules (MPMs). Each of these types of amplifiers can be used in electronically steered arrays. Each has its particular limitations constraining its ability to achieve desired power levels at sufficiently high frequencies, within the element-to-element spacing constraints at the antenna surface. VE devices and MPMs are impacted by the challenge of meeting severe size constraints imposed by the shrinking size of a half-wavelength as frequency of operation increases. For active apertures, when both vertical and horizontal polarization is required, practical size considerations limit VE applications to frequencies of about 9 GHz and below based on the size of the VE power booster alone. SSAs, while physically small, have struggled to overcome problems of low power and low efficiency. The advent of WBG microwave power amplifiers promises to alleviate these difficulties although others may arise (e.g., adequate thermal management). To meet the power requirements for the combined functionality, either extremely advanced VE amplifiers (not yet demonstrated in such small sizes) or WBG semiconductor devices are believed to be necessary.

The Army's emerging, highly-mobile, lightweight, flexible Future Combat System (FCS) will require that radar, communications, and electronic warfare functions be collectively performed at performance levels currently available from individual tactical systems in inventory. The combining of multi-modes and multi-function capabilities in a single system has considerable merit in situations where platforms are large enough to accommodate the desired configurations. Sub-array architectures in the 1-18 GHz frequency band provide sufficient lattice dimension to make them compatible with MPM RF sources. A sub-array architecture, however, intrinsically limits the instantaneous bandwidth of the system even though amplifier bandwidth may be more than sufficient for a given phase shifter setting. The disadvantages of a sub-array architecture include an increase in the transmission loss between the amplifier and the radiating element and increased noise floor compared to an element level active array. This later problem can be mitigated by the use of an active receive array embedded within a passive transmit array. MPMs and MMPMs have demonstrated bandwidth and

power levels necessary for use in the FCS system. However, additional computer modeling and simulation will be required to develop advanced MPMs and MMPMs that can reach the theoretically achievable high efficiency and reliability levels that are needed for the tactical light weight systems expected to be used to implement the highly mobile and transportable FCS. For general multifunction applications requiring greater-than-octave bandwidth, additional computer modeling and simulation will also be necessary to develop improved VE devices, in order to effectively control spurious signals. With the maturation of high power WBG amplifiers, SS approaches to these systems may also be viable.

Solid-State	Vacuum Electronics
• SSAs, while physically small, have struggled to overcome problems of low power and low efficiency. The advent of WBG microwave power amplifiers promises to alleviate these difficulties but others may arise (e.g. thermal management).	• VE devices and MPMs are impacted by the challenge of meeting severe size constraints imposed by the shrinking size of a half-wavelength as frequency of operation increases. When both vertical and horizontal polarization is required, practical size considerations limit VE applications to frequencies of 12 GHz and below. • The Army's Future Combat System (FCS) RF systems will require that radar, communications, and electronic warfare functions be collectively performed at performance levels currently available from individual tactical systems in inventory. Sub-array architectures in the 1-18 GHz frequency band provide sufficient dimensional tolerance to make MPM RF sources compatible with active arrays where a sub-array architecture is implemented. A sub-array architecture, however, intrinsically limits the instantaneous bandwidth of the system, even though amplifier bandwidth may be more than sufficient. MPMs and MMPMs have demonstrated bandwidth and power levels necessary for use in the FCS system. However, additional computer modeling and simulation will be required to develop advanced MPMs and MMPMs that can reach the theoretically achievable high efficiency and reliability levels that are needed. • For general multifunction applications requiring greater-than-octave bandwidth, additional computer modeling and simulation will also be necessary to develop improved VE devices, in order to effectively control spurious signals.

Table 6.11. Summary of SS and VE Applications to Multifunctional Systems

6.8. *GENERAL FINDINGS*

- The members of the Ad Hoc Solid-state and Vacuum Electronics Tri-Service Committee have agreed that substantial funding shortfalls exist and should be corrected.
- The total budget for VE and SS Applied Research is below critical mass (i.e., it is too low to sustain either technology and does not allow for any opportunistic investment).
- The continuing advances in VE technology present significant opportunities to respond to future military needs.
- Recent and potential breakthroughs for (SS) WBG semiconductor materials and devices are expected to revolutionize some aspects of electromagnetic systems warfare
- Just as the DARPA MIMIC and MAFET programs provided the enabling capability to field near term GaAs-based E/M systems, WBG technology is required to enable the next generation of E/M systems such as TBMD and multifunctional systems that provide reduced radar cross-section and lower life cycle costs. There is however, no such technology maturation program for WBG components.
- Since WBG materials and device technology compete with VE and other solid-state technologies, and the overall budget is so severely limited, it is impossible to adequately fund this emerging area under the present programmatic and funding constraints within the Services.
- The funding level for VE is currently set at $4.5 M for FY02 by the Navy, the Tri-Service Reliance lead Service, down precipitously from $12M in FY98 and $10 M in FY00. This FY02 funding level will create program instability; the program will no longer be capable of addressing the Services' pressing needs for this technology.
- Under the above situation the Navy cannot provide the Army or the Air Force with S&T support for VE, as required by long-standing Defense Reliance agreements.
- Present VE based radars could significantly improve their ability to operate in the presence of clutter and jamming if multiple beam amplifiers are developed. Using advanced CAD capabilities, VE amplifiers could be developed that have significantly greater reliability, efficiency, phase stability, and generally enhanced performance. New material developments will also required to enhance device performance and enable new device concepts.
- Reprioritizing existing funding is totally ineffective in light of the current total budget shortfall for RF power components S&T. It would probably destroy the DoD VE base while not generating enough additional funds to move WBG semiconductor materials and devices ahead substantially.

- Since DARPA has eliminated its Electronics Technology Office, DoD funding for SS microwave and millimeter wave amplifiers has fallen precipitously. The continuation of present SS funding levels will virtually insure that new electromagnetic concepts such as multifunctionality and Navy TBMD will not materialize.
- Burgeoning millimeter-wave applications require further maturing of the GaAs area, investment in InP materials, investigation of frequency extensions of WBG devices, and devices and exploitation of vacuum electronics opportunities.
- Active aperture arrays are intrinsically capable of providing lower phase noise floors than are corporate-fed arrays; where the noise floor is a consideration for high data rate communications or for tracking targets in the presence of severe clutter or jamming, active aperture architectures must be considered.
- Advanced military platforms require conformal electronics based on flexible array concepts and interconnects.

7. OTHER RELEVANT ISSUES

7.1. *INDUSTRY OUTLOOK*

Vacuum Electronics

The outlook for the U.S. vacuum electronic device industry was explored in 1997 by OSD/OUSD(AT&L). Its conclusions were: (1) the industry is defense critical, (2) the industry's commercial base does not support advanced defense needs, and (3) reductions in R&D spending cannot not be tolerated without significant adverse impact. Similar to the aerospace industry in the mid-90's, the VE device industry has recently begun to consolidate to a few large competitors. For example, Litton Industries is selling its defense sector to Northrop-Grumman. As a result, Northrop-Grumman's Rolling Meadows VE facilities, noted for superior R&D capabilities, will join forces with Litton's San Carlos VE manufacturing resources. This will strengthen both organizations. The VE RF power tube industry remains critical for the present and future defense of the nation.

Solid-state

In the semiconductor SS industry, RF WBG technology infrastructure is in its infancy and is currently dominated by one manufacturer. The technical focus of commercial sector efforts for the WBG industry is lighting, display, and laser devices for information technology applications. It is currently envisioned that a commercial market may not emerge for the high power RF devices that are needed by the DoD. Thus DoD investment is critical at this early stage of development. Although some of the commercial WBG opto-electronic technology developments, particularly of materials, may be leveraged for military RF device applications, it is clear that unless the DoD invests in the RF device area there will be little incentive for industry to do so. The DoD is currently funding two primary SiC device manufacturers and was funding two GaN device manufacturers until one was bought out by the other. In addition, at least four aerospace corporations are now conducting internally funded WBG semiconductor RF device and circuit programs. Also, there are several small start-up companies funded under SBIR programs, and private funds, that are developing WBG RF technology. For GaAs and InP MMICs, merchant semiconductor production emphasis has shifted overwhelmingly toward the commercial wireless marketplace. Advanced silicon (e.g., SOI) and SiGe technologies are also used to produce commercial wireless products that operate at microwave frequencies below about 2.5 GHz. These technologies do not meet the performance demands of modern DoD electromagnetic warfare systems.

7.2. *TALENT BASE*

The science and engineering talent base is being eroded as a result of several factors: (1) the financial attraction of the high technology private sector (2) the uncertainty of future DoD funding for advanced applications, and (3) the aging of the S&T talent pool. This latter situation is exacerbated by reductions in university funding.

The talent base, if not replenished, will not be able to regenerate itself without major investment; should the DoD require RF amplifiers in the future that have high power, high efficiency, high phase stability, and are available at relatively low cost to enable new platform capabilities it may be unable to obtain them. Without significant attention to this issue, new operational capabilities will not be possible and our fighting forces will no longer have a technological edge over their adversaries. A significant number of talented younger scientists and engineers have become members of the wireless community and may never be available to the military marketplace.

7.3. *OFF-SHORE COMPETITION*

Many competitors to the U.S. vacuum electronic device industry are supported directly or indirectly through aggressive R&D policies of foreign governments. The trend for U.S. OEMs is to go to off-shore vacuum electronic device vendors. The potential consequence of this approach is to place the U.S. military in an exposed position during time of conflict and risk price increases as domestic competition wanes. WBG technology as little as 3 years ago was dominated by the USA. Today, there is greater SiC investment in Europe than in the USA and there is greater GaN investment in Japan than in the USA. The GaAs MMIC industry base, for wireless applications, is still primarily CONUS based, but with the availability of tools and material worldwide this could change. Technology developed off shore will be available to any country with sufficient funding to purchase it. If we do not significantly accelerate our pursuit of advanced VE and WBG SS amplifier technology, our forces could find themselves having to operate with technologically obsolete E/M capabilities within this decade.

7.4. *INFRASTRUCTURE*

Solid-state

A significant shortfall exists for supplying the solid-state modules required for RF transmitters in military systems. Since military applications constitute roughly only 2-5% of the total market for GaAs based transmitters, commercial foundries have little interest in producing power amplifiers for those applications. COTS MMICs produced by the approximately 10 domestic commercial foundries are, generally, lower frequency, narrower bandwidth, and lower power designs than those needed for DoD use; these foundries are geared to support the cellular phone and wireless markets. The processes used by these commercial foundries are often not capable of meeting the military performance requirements even when custom integrated circuit designs are used. Consequently, MMICs for military systems are presently supplied mainly by 3 or 4 captive foundries that are owned by major aerospace companies. Custom MMICs produced by these foundries often have low yields (10-50%) and this situation, combined with relatively low quantities produced, results in a very high per-unit cost (as discussed in Section 6 above.) This situation is magnified in the case of InP devices that are required for millimeter wave transmitters; for these devices, only 2-3 sources exist. As an increasing number of systems that rely on GaAs and InP MMIC technologies come into production over the next 5 years, resultant demand for MMICs will tend to approach

the production capacity of the captive foundries. This will help to lower the per unit cost of this technology. In the interim, these foundries are using excess capacity to fill commercial orders.

The infrastructure available for producing wide bandgap SiC and GaN based transmitters is still at an embryonic stage of development. Although there is a large and expanding commercial market for LEDs and lasers based on GaN, (>$400M in 1999 and projected to be >$4B by 2009) the material requirements for these devices (N-doped) are different from those required by the RF transmitter market (semi-insulating). There is an emerging market for high purity SiC material for gemstones. DoD can gain some leverage from this market since the processes necessary to grow high purity gemstone material are also applicable to the production of semi-insulating SiC substrates. However, the crystallographic structure of gemstones is 6H whereas RF devices with the highest levels of performance are fabricated upon a 4H crystalline structure. The initial commercial markets for SiC devices will be narrow band, low frequency (1-6 GHz) and high linearity for wireless base stations. Devices fabricated for these commercial applications will not meet DoD system needs, for which higher power and wider bandwidth, as well as pulsed operation are required. Potential commercial markets for GaN devices include 28 GHz Local Multipoint Distribution System (LMDS), Wireless Local Loops (WLL, collision avoidance radar, and satellite links. These are also narrow bandwidth, lower power CW applications, compared to potential DoD system uses.

WBG semiconductor devices are also important for power electronics applications such as might be needed for the vehicles of the Army's FCS and the Navy's All Electric Warship. In particular, power devices such as free wheeling diodes and switching transistors , fabricated from SiC materials, offer the advantage of being able to handle very high voltages (> 6 kv) for power conditioning and control compared with other semiconductor technologies. Commercial applications envisioned that require this level of power handling capability include electric vehicles, ships, and cross country transmitting equipment.

Vacuum Electronics

Military-unique microwave vacuum electronic devices are based on advanced technology to achieve efficiency, power, bandwidth, and reliability. DoD considers certain microwave vacuum electronic device technologies critical to military effectiveness and has identified them as such in its Military Critical Technologies List. For this reason, the U.S. Government controls the export of microwave vacuum electronic device technology and products, and limits procurement of certain military-unique microwave tubes to domestic sources.

US microwave vacuum electronic device sales have declined, primarily due to reductions in defense spending. Historically, military purchases have accounted for the majority of world-wide microwave vacuum electronic device sales. Between 1985 and 1995, U.S. microwave vacuum electronic device industry sales world-wide declined from $671 million to $256 million (54% of worldwide sales) primarily as a result of reduced

DoD purchases. With the end of the Cold War, governments everywhere have cut back on military spending. Most industry experts believe that U.S. manufacturer microwave tube sales bottomed out in 1994. However, increased commercial demand may lead to increased sales of microwave tubes for telecommunications satellites and ground stations. Both U.S. and foreign manufacturers are pursuing commercial opportunities throughout the world to compensate for flat military demand.

Total R&D spending by U.S. microwave power vacuum electronic devices manufacturers declined from $114 million in 1985 to $26 million in 1995. The decline in R&D was driven by significant decreases in R&D funding from DoD and civil agencies (from $54 million in 1985 to $7 million in 1995). Corporate spending to develop new products and processes, funded by microwave vacuum electronic device sales, also decreased significantly (from $44.5 million in 1985 to $14.4 million in 1995). U.S. microwave vacuum electronic device manufacturers have indicated that corporate R&D investments are being directed increasingly at commercial applications.

Today, seven domestic companies produce microwave RF power vacuum electronic devices. Although all manufacture and repair microwave power VE devices, four companies account for the vast majority of U.S. industry sales. CPI, Litton/A Subsidiary of Northrop Grumman Corp., the Teledyne Vacuum Technology Business Unit, and the Boeing Electron Dynamics Division collectively account for about 49 percent of world-wide microwave vacuum electronic device sales, 91 percent of U.S. manufacturer sales, and 93 percent of sales for DoD applications. CPI and Litton/A Subsidiary of Northrop Grumman Corp. manufacture a full range of microwave vacuum electronic devices. Each of the remaining manufacturers generally specializes in one or two tube types.

Although the quantities of microwave vacuum electronic devices purchased for new DoD systems have declined, the number of microwave tube types in fielded military systems has not declined; and DoD requirements for technical support for fielded systems have not declined. More than 270 weapon systems contain a total of more than 180,000 microwave vacuum electronic devices, and many of the systems employ three to five different tube types. Some systems contain more than 200 microwave vacuum electronic devices. At the time of the OSD Industrial Infrastructure Study of the Microwave Tube Industry in 1997, it was concluded that industry sales and investment trends had not adversely impacted the U.S. microwave vacuum electronic device industry such that direct DoD intervention was required to maintain national security. The study concluded that microwave vacuum electronic device industrial capabilities were adequate to meet DoD requirements. However, the study noted that further declines in DoD sales or DoD R&D investments could alter this assessment. Since 1997, DoD R&D investment in vacuum electronics has declined from approximately $17M in FY97 to $7.5M in FY01.

8. PROGRAM FOCUS AND JUSTIFICATION

Program focus and justification is presented for SS technologies and VE technologies. These efforts are consistent with the Tri-Service RF Power Technology Roadmaps presented in Appendix A.

8.1. *APPLIED RESEARCH (6.2) PROGRAM (VE)*

As a general rule, uncontested opportunities exist for devices that are improved or enabled by S&T investment in VE for meeting the requirements of high power millimeter wave applications and those of other applications related to single function systems where cost is an important consideration. Applications using corporate-fed arrays and parabolic antennas will generally make use of VE device technology. Applications for which large active aperture arrays are required will probably make use of SS technology. A trade-off exists as a function of aperture size for active apertures. The solid-state T/R module offers advantages for larger aperture systems while vacuum electronics become more competitive in limited and reduced aperture systems (e.g. pods).* Additional system types will select from either VE or SS power amplifiers on a case-by-case basis. The Applied Vacuum Electronics Research Program has six areas of technology emphasis, including two that provide support all of the technical activity. The areas are:

1. Multiple-beam amplifier (MBA) technology suitable for supporting high-power applications such as the AEGIS SPY-1 upgrade
2. Linear wideband amplifier technology for electronic warfare and communication applications;
3. Slow-wave millimeter-wave amplifier technology for airborne radar and missile seeker technology;
4. High-power millimeter-wave gyro-amplifier technology at K_a- and W-bands
5. Modeling and simulation activities focused on the development of advanced physics-based codes; and
6. Sub-component technology including the extremely important areas of materials and electron emitters

8.1.1. MULTIPLE-BEAM AMPLIFIERS

The multiple-beam klystron (MBK), a variant of multiple-beam amplifier (MBA), has a 50 dB noise performance advantage over the CFA currently used in the SPY-1 radar. It represents a viable option for improving SPY-1D(V) performance in high-clutter environments and against small-cross-section targets at large distances. In addition, it is capable of high duty factor (10%), long pulse length, and extended bandwidth operation. Although the current Navy Radar Roadmap does not provide for this upgrade, studies are currently being conducted by NAVSEA PMS-450 to better understand the potential of the MBK.

Most importantly, this technical thrust would create an MBA technology base for a broad class of defense applications, providing upgrade paths to radar systems other than the SPY-1D(V), e.g., the SPQ-9B, missile seeker applications, and for new communication systems where wide bandwidth, linearity, and compactness (efficiency) are critical considerations. The SPQ-9B, is however, scheduled for replacement by the solid-state MFR radar. The lower phase noise of the MBA amplifiers could provide the basis for higher spectral utilization in future single-function communications systems.

8.1.2. Linear Wideband VE Amplifiers

This project provides the continuing research and development required to simultaneously achieve advances in linearity, bandwidth, and power, to satisfy both communications and electronic warfare system needs. It will also lead to dramatic size and weight improvements. Evolving communication systems need high data rates and high linearity, and make use of advanced modulation schemes. Evolving electronic warfare systems will require high-power, ultra-wide bandwidth, and linearity. As radar systems of our adversaries begin to use sophisticated modulation schemes, our EW systems must be able to counter them and to do so must exhibit a very high level of phase stability. All requirement sets are frequently coupled with the need for compactness, high efficiency, and affordability. One of the most successful recent VE programs has been the Microwave Power Module (MPM). For this device, the final stage of amplification is provided by a low-gain, high performance traveling wave tube (TWT). The advent of use of WBG drivers in these MPMs should significantly improve their operational performance.

Millimeter-wave amplifiers have the potential to provide the large fractional bandwidths necessary to meet high data rate communication system requirements. New electro-dynamic structures will be examined by computer simulation to enhance amplifier linearity while maintaining high efficiency. Structures that will be analyzed include tapered helix TWTs and transverse field TWTs. The latter will be based on a structure that promises high linearity, low noise, and wide bandwidth for high-power TWTs.

For electronic warfare needs, efforts will focus on expanding the power-bandwidth capability of MPMs and MMPMs. Ultra-wideband MPM (UWBMPM) technology must be further enhanced to provide better fundamental frequency power amplification (i.e., reduction of harmonic power). To this end, a combination of dispersion control and MMIC harmonic injection circuitry will be applied over the 2- to 18-GHz frequency range. In the 18- to 40-GHz frequency regime, MMPM technology must be enhanced to provide higher power across the band. For all of these efforts, computational simulations will point the way toward enhanced linearity, efficiency and power-bandwidth extension.

8.1.3. Millimeter-Wave Amplifiers

Extended interaction klystron (EIKs) and coupled-cavity TWTs (CC-TWTs) are important devices for use in future millimeter-wave radar systems. Planned device

development will focus on CC-TWT and EIK amplifiers with enhanced bandwidth, efficiency improvements, and weight reduction. Through the use of advanced materials and improved design codes, these MMW devices will be optimized for their respective applications.

Coupled-cavityTWT development at W-band will be continued. This will include completion of a 1-kW (peak), 100-W (average) power, 4 GHz bandwidth device at 94 GHz for SAR and ISAR radar applications. EIK amplifier development will focus on 94 GHz 1 kW (peak) power EIKs which have 2.4-GHz bandwidth. In addition, work will proceed on K_a-band EIKs for UAV-based SAR applications. Critical issues are circuit thermal design, broadening of circuit impedance matching circuits to achieve wide bandwidth, and compact design.

8.1.4. HIGH-POWER MMW GYRO-AMPLIFIER

High-power millimeter-wave amplifiers are needed for use in a variety of surveillance and instrumentation radars. The gyro-amplifier is capable of delivering adequate power, in the millimeter-wave band, for these missions. The MMW CC TWT, described in the paragraph above, could also be used in a sub-array-configured version. It would provide a lower noise floor and higher dynamic range of operation for the radar. The gyro-amplifier, and in particular the gyro-TWT amplifier, yields unprecedented power in millimeter-wave bands and could be used for upgrades to the Kwajalein millimeter-wave radar (K_a-band and W-band) for TBMD and NMD testing, as well as for space surveillance and space-object identification from upgraded Haystack, HAX, or other radar assets.

The Air Force Space Command upgrade of the MIT/LL X-Band Haystack Radar with the W-band HUSIR radar for ultra wideband satellite imaging could utilize the development of the W-band gyro-TWT. Such an upgrade would permit the imaging and space object identification of the increasing number of orbiting micro-satellites. The Army's interest in this technology is for the upgrade of the Kwajalein Missile Range instrumentation radar to support greater S/N on target for better kill assessment, miss point determination, and target micro-dynamics measurement. Some interest in this technology is centered at present on the WARLOC radar being demonstrated by NRL. Application of this radar and development of the K_a-band gyro-TWT for Navy TBMD range testing is supported by NAVSEA through PMS 452. Even though the total DoD "market" for such devices is small, the capability afforded by the technology justifies a continued reasonable S&T investment.

8.1.5. VE DEVICE MODELING AND SIMULATION

The principal goal of this technical thrust is to reduce VE device development time and cost by achieving first-pass design success. This would be accomplished through the application of simulation-based design methodologies rather than by continuing to use the current cyclic build-and-test methodology. Specification of the

design tools for the modeling and simulation (M&S) suite is based on requirements derived from interactions with U.S. vacuum electronic device manufacturers.

Specifically, the program addresses:

- Accuracy deficiencies of predictive capabilities for addressing both 2- and 3-D stability-related problems in helix and coupled-cavity TWTs and klystrons;
- The lack of theoretical models capable of addressing internal reflections in the amplifier; these can create unacceptable gain and phase variations over the frequency range of operation;
- The strong requirement for a time-dependent ability to analyze device performance;
- The need for integration of the design tools; and
- The need for a systematic validation of design tools.

The highest priority is to improve capabilities for analyzing helix TWTs. However, increasing effort will be applied to the analysis of coupled-cavity TWTs, extended interaction klystrons (EIKs), and multiple beam klystrons (MBKs).

The parametric CHRISTINE 1D/3D codes will provide small and large signal multi-frequency models for helix TWT design In addition, CHRISTINE 3D will be integrated with the magnet circuit code mPPM/lesPPM and the gun/collector code MICHELLE.

The need to deal with specific digital protocols for communications drives the requirement for time-dependent modeling. Near-term plans call for the inclusion of time dependence in the helix TWT large-signal model, with later development of new models for coupled-cavity TWTs, klystrons, and EIKs.

A new 3D finite-element gun and collector modeling code, MICHELLE, has been designed specifically to address the shortcomings of current beam optics simulation and modeling tools. The proposed program specifically targets the problem classes of gridded-guns, multi-beam devices, and anisotropic collectors.

8.1.6. Sub-Component VE Device Technologies

Limitations associated with currently-available materials continue to be key barriers to cost and performance improvements for VE devices, particularly as commercial and defense needs expand into the millimeter-wave frequency regime. In this frequency range decreasing device dimensions lead to increasing power and energy densities. The four areas in this project have potential for significantly impacting a broad range of military needs. Eleven major DoD platforms are affected by the decreasing domestic availability of BeO-SiC. CVD diamond support technology will benefit a number of systems requiring high bandwidth and average power. Improved magnetic

materials and magnetic circuits will result in more than a 3X reduction in weight (compared to electromagnets)

This project has four key areas:

- Lossy Dielectrics. Electromagnetically lossy dielectrics are used extensively to suppress instabilities, increase bandwidth, and reduce reflections. BeO-SiC ceramic composites were the materials of choice for high-average-power applications. However, increasing concern about the health/environmental risks associated with beryllium-based products contributed to the termination of all domestic production of BeO-SiC products as of March, 1999. There is a clear and compelling need for a replacement material. This R&D plan addresses this need for a high thermal conductivity, electromagnetically lossy replacement for BeO-SiC.
- CVD Diamond Supports. Electrically-insulating high-thermal-conductivity supports are used in helix-TWTs and multi-stage depressed collectors. CVD diamond, which has the highest thermal conductivity and hardness of all known materials, will be developed to replace currently used BeO and APBN supports.
- Rare-earth Permanent Magnet Materials. Magnetic materials and magnetic systems that provide adequate beam confinement while meeting system-specific volume and weight requirements will be developed
- Advanced Emitters. Scandate cathodes with current densities of 10 to 50 A/cm^2 at reduced temperatures will be realized. This development activity coupled with innovative fabrication techniques such as pulsed laser deposition, will be supported by scandate development, testing, and transition to industry.

8.2. *ADVANCED DEVELOPMENT (6.3) PROGRAM*

8.2.1. MPM & MMPM

Many EW systems (e.g., AN/ALQ-211, towed decoys, IDECM upgrades, and UAV sub-systems) will be in inventory or development beyond 2025. The Suite of Integrated RF Countermeasure (SIRFC) includes both RF and EO jammers. MPMs and MMPMs represent the near- and mid-term choice for SIRFC RF because of their small size, multi-octave bandwidths, high power, and overall high efficiency. Additional enhancements to current capabilities will be needed to meet system requirements.

Specifically, Advanced Development programs may be needed in the areas of:

- IDECM MPM Upgrade Affordability. The Applied Research program thrust under MPMs is currently aimed at completing the Ultra-Wideband MPM (UWBMPM) that will provide 51 dBm of power across the 2- to 18-GHz band. UWBMPM is being integrated into a pod-based array, by the U. S. Air Force. However, no funding is available for UWBMPM cost reduction. In a related program, the U. S. Air Force is investing MANTECH funds to produce a limited

number of MPMs that operate from 4.5- to 18-GHz. These will be used in the HPFOTD Towed Decoy program. These three related efforts would ideally be supported by a common Advanced Development program that would integrate the benefits of continuing performance enhancements into a high-volume acquisition program.

- Dual-Mode MPMs and MMPMs. The technology base for high peak and moderate average power amplifiers that meet the needs of synthetic aperture radar transmitters must be transitioned to support tactical UAVs (TUAVs). Powers of up to 200 watts (CW) and 2-5 kW (pulsed) over multi-octave bandwidths at frequencies through millimeter-waves are essential. This capability will also provide upgrade paths for such systems as ALQ-131, ALQ-135, ALQ-184 and ALQ-161. Currently UAVs are limited in their mission capabilities and must return to base to be outfitted with changed E/M systems for each change of mission. Newer UAVs, under consideration, may use multifunction active aperture scanned arrays. For these arrays, SS devices will be viable competitors to VE.
- Linear Wide-band MPMs. Efficient, highly linear, narrow-band MPMs and MMPMs will be required for next- generation communication systems. New design codes from the Applied Research program can be applied for fast turn-around optimization. Solid-state amplifiers—particularly WBG types – will become very competitive at frequencies below 26 GHz.

8.2.2. Millimeter-Wave Amplifiers

Periodic permanent magnet (PPM) coupled-cavity TWTs and extended interaction klystron amplifiers (EIKAs) operating in K_a- and W-bands will provide options for airborne ground moving target indication (GMTI), non-cooperative target recognition (NCTR), discrimination, targeting, and battle damage assessment (BDA) an airborne platforms (aircraft, UAVs), as well as in missile seekers.

Compact millimeter-wave TWT technology will be implemented in millimeter-wave power modules (MMPMs) to support Navy interests in high-resolution all-weather imaging radar, secure communications, electronic decoys, and threat surrogates and simulators.

8.2.3. Test Range Gyro-Amplifiers

Those responsible for the Army's K_a/W-band millimeter-wave radar at Kwajalein Missile Range, run by MIT/LL and Raytheon, and the managers of the Navy's Pacific Missile Range Facility, Kauai, Hawaii, have both indicated a need for capabilities afforded by gyro-amplifier technology. Devices tailored to specific range needs will be developed with goals of wide bandwidth (4 to 6 GHz) at high power levels (20 kW average, 100 kW peak) in K_a -band, and ultra-wide bandwidth (up to 8 GHz) in W-band for Air Force Space Command space surveillance needs.

8.2.4. Multiple Beam Klystrons

The 6.2 effort culminating in the demonstration of a prototype S- band MBK will provide an option for the replacement of the amplifier chain (CC-TWT and CFA) in the current SPY-1. The MBKs will provide an amplifier option for the SPY-1D to transition into the NTW Block II Backfit Program in about FY07. The IOC for this demonstration of capability is FY-03. A follow on program for Cruiser Conversion would transition the MBK into the SPY-1B.

8.2.5. Industrial Infrastructure

The purpose of this program is to transition, to the industrial base, technology that has been developed under Basic and Applied Research programs, as well as under other programs such as the ONR SBIRs. The components of this program are described below.

- High-Thermal Conductivity, Electromagnetically Lossy Dielectrics (AlN vs. BeO)
- CVD Diamond Supports (High thermal conductivity material)
- Rare-earth Permanent Magnet Materials (Light weight structures for electron beam focusing)
- Advanced Emitters (High current density Scandate long life cathodes for satellite and EW)

8.3. *SOLID-STATE APPLIED RESEARCH (6.2) AND ADVANCED DEVELOPMENT (6.3)*

As a general rule, uncontested opportunities exist for solid-state amplifiers in fuzing applications and in applications wherein simultaneous multifunctionality is required. To a lesser extent, in the future, the requirements of all multifunctional radar systems and active apertures that operate at frequencies below 25 GHz in the near term and 50 GHz in the longer term are expected to be met by SS technology. Still other opportunities exist. However, SS technology is generally not the technology of choice for applications that make use of corporate-fed arrays or parabolic antennas.

Tri-Service investment in RF SS components for military applications is focused on (1) high power and high efficiency amplifiers for transmitters, (2) spurious-free high dynamic range receivers, (3) SS devices and ICs that can operate at frequencies from a few GHz to above 40 GHz, (4) stable frequency sources & clocks and (5) highly capable and versatile antennas. For the purpose of this document, item (1) is of primary relevance; it is the only one for which SS competes directly against VE. However, item (3) enables versatile active aperture SS systems that have enhanced versatility. The DoD SS portion of the high power & efficiency transmitters area is focused upon wide-band amplifiers for shipboard active arrays (e.g., AMRFS, DD21), advanced multi-mission UAV/UCAVs (e.g., Global Hawk-follow-on), ultra-efficient amplifiers for space, high power amplifiers for search (e.g.,TPS-75), the USMC MRRS, the Navy TBMD mission

and volume search radar mission, millimeter wave amplifiers for missile seekers and precision munitions (e.g., BAT, TERM, Hellfire, Hammerhead, LOCAAS,) and communications. The current tri Service 6.2 investment is about $6.7M/year.

GaAs

This material is used to provide the current baseline SS approach for DoD microwave and millimeter-wave frequency power amplifiers. GaAs technology (materials, devices, circuits, processing, life & reliability testing) has matured to a level approaching that of silicon. This was achieved through a large infusion of defense funding (MIMIC and MAFET program funding). It is also currently the material of choice for the wireless community, primarily for use in mobile applications where the high efficiency and ability to operate from a single voltage power supply make GaAs HBTs the devices of choice over silicon bipolar MMIC's. Many DoD systems contain GaAs MMIC's. However only a handful of GaAs foundries remain that are both capable of and have the economic incentive to produce military grade MMIC's. It is imperative that funding be provided for continued support of this technology. This will allow the realization of incremental performance upgrades and guarantee a military market sufficient to keep qualified vendor fabrication lines operating at reasonable levels of production. It is the lowest cost of all the microwave/millimeter wave technologies and is envisioned to remain so because of its mature status and the availability of large diameter GaAs substrates. Many CAD tools are available for GaAs device and circuit design. Many of these are also used by the commercial sector for wireless circuit design. Available models are excellent, making possible accurate performance simulation. As a result, first pass design success can often be achieved. Flexible manufacturing making use of large volume commercial product lines is a possibility for satisfying military requirements. Low MMIC cost is a substantial contributing factor for continued innovative application of this technology. Reliability, reproducibility, and yield of GaAs MMICs are all excellent and most GaAs MMIC fabrication lines make use of statistical process control (SPC) to enhance both yield and performance. The current DoD investment opportunity in this area is primarily related to further driving down the cost of GaAs MMICs that are needed for use in military systems.

InP

Although not as mature as GaAs, InP technology has reached a reasonable level of development during the last decade. Current fabrication status for InP devices and MMICs includes various 3 and 4 inch diameter wafer product lines and the likelihood of two 6 inch diameter wafer pilot/production lines beginning operation in the near future. The first InP commercial RF device foundry opened in 2001. Applications for InP devices and MMICs include both millimeter wave electronic systems and opto-electronic (fiber optic) systems. The prime attributes of this technology are its ability to operate at frequencies above 30 GHz and its ability to achieve the excellent level of efficiency necessary for power amplifiers in transmitters. This is especially important for dense millimeter arrays, where heat removal will be a problem. F_t's of over 200 GHz have been reported. However, InP devices and MMIC's are currently significantly more expensive

than GaAs devices and MMICs because of their relatively low fabrication yield and other process-related problems. Research is required to lower the cost of these components. One approach to reduced cost, which has been explored, is to grow InP epitaxial layers with high indium content on GaAs substrates. The metamorphic HEMTs (MHEMTs) produced in this way benefit from the lower cost and easier availability of GaAs substrates. Future work is needed to bring this approach to an acceptable level of maturity. In addition, research will be required to produce accurate millimeter wave MMIC models, adapt GaAs design tools, determine device reliability, and establish other figures of merit that are the hallmarks of a mature IC process.

SiC and GaN (Wide Bandgap Semiconductors)

The newest additions to the family of semiconductor materials that have high performance capabilities at microwave frequencies are SiC and GaN. They are at a relatively immature state of development but have the potential to revolutionize microwave electronics by enabling new military operational capabilities. To present the proper program motivation, focus and justification for further research in this area, the findings from a DoD AGED Special Technology Area Review (STAR) entitled "RF Applications for Wide Bandgap Technology" held in April 2000 are offered below. They are augmented by the recommendations of this study.

Materials

The lack of a lattice matched substrate for GaN results in a high dislocation density (typically $\geq 10^8$ cm^{-2}) in present AlGaN HEMTs. The presence of these dislocations appears to have little detrimental impact on the two dimensional electron gas (2DEG) mobility in HEMTs, largely due to the large sheet electron density ($>1x10^{13}$ cm^{-2}) that screens the dislocations. The effect of dislocations on device reliability is unknown. Subsequent to the AGED STAR, GaN films have been grown on 4" diameter silicon wafers by a modified pendeo-epitaxy process that has lowered dislocation densities to 10^6 cm^{-2}. The silicon substrate is etched away after device processing. If DoD is to exploit this technology, a GaN materials maturation program similar to that of the GaAs MIMIC program will be required.

The size, quality, and availability of semi-insulating 4H SiC substrates are, presently insufficient to support large DoD system programs. There is a DoD Title III program addressing SiC (both 4H and 6H) substrate size and quality; however, it does not directly address semi-insulating material (its focus is on n-type wafers) required for microwave devices. At a minimum, three-inch diameter (four-inch diameter is preferred) 4H SI-SiC is needed to meet T/R module cost goals for system insertion of WBG amplifiers. Presently, only two-inch SI-SiC semi-insulating wafers are commercially available, and, in relatively large quantities, from only from one supplier. Subsequent to the AGED STAR, a small business has learned how to increase the diameter of SiC boules without introducing polytypism inclusions in the periphery region. In order to be able to use SiC for high power microwave amplifiers, DoD must significantly increase its effort to synthesize larger diameter semi-insulating SiC boules.

WBG epitaxy needs further improvement and a fundamental understanding of background doping, large area uniformity, and reproducibility must be attained. As wafer diameter increases, development of larger area epitaxial growth processes must also be addressed. This S&T requirement is largely 6.1 in nature, but certain aspects such as heterojunction development must be incorporated into 6.2 programs.

Silicon Carbide	Gallium Nitride
• At a relatively advanced stage of development – SiC substrates are available ⇒ Need larger diameter with fewer defects ⇒ Need ability to control conductivity ⇒ Need n, p and semi-insulating material – SiC epitaxy needs further development ⇒ 1×10^{15} cm^{-3} doping possible ⇒ 1×10^{14} cm^{-3} background doping ⇒ current doping uniformity is 10% and current thickness variation is 3% for 2" diameter substrates—improvements are needed	• At an immature state of development – No lattice-matched substrates are available—need to determine viable techniques for producing them – GaN epitaxy is at a very early stage of development ⇒ 1×10^{16} cm^{-3} doping possible

Table 8.1. Current State of SiC and GaN Materials

• High quality SiC epitaxy achievable
• Device ready epi-quality—Cree, Sterling and TDI are selling thick epi-films
• Commercial chemical vapor deposition equipment for sale—Emcore and Aixtron
• Demonstrated proof-of-concept power devices—Diodes with 5500 volts breakdown; high power MESFETs and SITs; Cree selling SiC MESFETS commercially

Table 8.2. Progress and Status of SiC Epitaxial Material

• Better doping control required—need better control and understanding of high resistivity layers; need better reproducibility and control for device applications
• Better substrates with low-dislocation density required
• Commercial epitaxial equipment for sale—Emcore and Aixtron (OMCVD); Riber, VG, EPI (MBE)
• Several companies and universities have demonstrated proof-of-concept power HEMTs—Cree, Nitres, UCSB, Cornell, HRL, NRL, Rockwell

Table 8.3. Current Status and Progress of GaN Epitaxial Material.

Devices

Wide bandgap (WBG) RF technology, based on SiC and/or GaN, offers the potential for a 10-fold increase in power at a given frequency compared with currently available GaAs technology. A small periphery GaN HEMTs has demonstrated a power density of 9.8 W/mm at X-band, seven times that of the best GaAs HEMTs. Large periphery (8 mm) AlGaN HEMTs have demonstrated 50 W (pulsed) of total output power at a power density of 6.5 W/mm. This is 10 times the power density of large periphery GaAs transistors.

The high operating voltage of WBG RF technology offers a potential efficiency advantage at the device level (PAE is equal to $(1 - 1/G)[(V_{br} - V_{knee})/(V_{br}) + V_{knee})]$ where V_{br}, is 10 times higher for WBG over conventional solid-state), circuit level (more efficient combining as a result of higher transistor impedance), and subsystem level (the higher local bus voltage enables more efficient prime power distribution and conversion).

This study recommends exploitation of the very high dielectric strength of WBG materials to affect more efficient, more linear class B, push-pull amplifier development.

SiC microwave devices (MESFET and SITs) presently have better total power performance than AlGaN HEMTs. The SiC devices are projected to be limited in frequency of operation to 10 GHz or below.

AlGaN HEMTs are projected to have superior efficiency over SiC MESFETs and InGaAs PHEMTs, at frequencies at least up to 30 GHz. Their superior efficiency over SiC MESFETs has been demonstrated, but that over InGaAs PHEMTs is only a projection. This study recommends additional development of ohmic contacts to reduce loss and improve the efficiency of these devices.

The large critical breakdown fields of SiC and GaN place the electrical limit of WBG transistors at up to a factor of two higher than their thermal limit. To gain full device performance, thermal management is critical. High efficiency amplifiers (such as push-pull Class B) using WBG transistors may not be thermally limited. This will enable higher efficiency operation (theoretical drain efficiency is 78.5 % for class B versus 50 % for class A). This study endorses the study of high efficiency amplifier circuit implementations implemented with WBG solid-state transistors.

Proof of principle SiC and GaN microwave devices with excellent performance have been reported, but the ability to reproduce them has not been confirmed and yield analysis has not yet been conducted. This study recommends a WBG technology maturation program to address these issues in the manner similar to that used previously by the GaAs MIMIC program.

The large polarization effects in the AlGaN/GaN materials system enable a new class of device structures for which channel charge is induced without additional extrinsic

doping. This results in a sheet electron density $>1x10^{13}$ cm^{-2} that is four times higher than that for a GaAs PHEMT.

Present GaN HEMTs generally have not incorporated recessed gates or pseudomorphic channels to improve their performance as was done for devices that use GaAs or InP technology. This may be an avenue for effecting future device improvements. This study recommends initiation of such development.

GaN HEMTs with 8-mm of gate periphery have been demonstrated that produce a pulsed output power of 51 W at 6 GHz (representing a power density of 6.5 W/mm); devices with 12-mm of gate periphery have produced a pulsed output power of 40 W at 10 GHz, and devices with 4-mm of total gate periphery have produced a cw output power of 20 W at X-band. A GaN MMIC with source vias has been demonstrated that delivered 20 W (pulsed) at 9 GHz. This study recommends an aggressive development of GaN MMICs.

SiC MESFETs with gate peripheries of 48-mm have yielded cw output powers of 80 W at 3.1 GHz; devices with a gate periphery of 12 mm have yielded pulsed powers of 30 W at 10 GHz.

Packaged SiC SITs have demonstrated pulsed power levels of up to 900 W at L-band. They have not been readily scaled to S-band operation. Research being conducted to achieve higher frequency operation is ongoing. This study recommends the initiation of low parasitic SiC SIT development to address S-Band requirements.

Microwave trapping effects are evident in WBG RF devices. These traps have been significantly reduced in the best devices, but this area requires more investigation. This study recommends a WBG technology maturation program to address this issue.

Limited reliability data exists for SiC microwave devices; none exists for GaN transistors. This study recommends a WBG technology maturation program to address this issue and to reduce risk for platform integrators.

AlGaN/GaN HBT performance is presently constrained by low p-doping, low hole mobility, and low minority carrier lifetimes in the base. Only DC results have been reported. This study recommends the initiation of research to lower the acceptor activation energy by introducing arsenic and/or phosphorous to GaN.

Realization of robust, low noise amplifiers (LNA's) based on AlGaN HEMTs may relax the requirement for protection circuitry (limiter circuitry) in receivers. Robust AlGaN LNA's are expected to have superior dynamic range, bandwidth, and a lower overall noise figure compared with those of conventional LNA's with protection circuitry. For example, AlGaN HEMTs have demonstrated a noise figure (NF) of 0.6 dB at 10 GHz with 13 dB of gain and a breakdown voltage of > 60V. The best InGaAs pHEMT NF at 10 GHz is 0.3 dB, but with a breakdown voltage of only $\approx$3V. The associated protection circuitry for the InGaAs pHEMT adds an additional noise figure of

0.5 to 2.0 dB,

depending on the protection requirements. Thus, their system noise figure exceeds that of the AlGaN device.

WBG RF technology offers a significant (-10x) power-bandwidth product advantage over Si, GaAs, and InP technologies as a result of high power density, high operating voltage, and high impedance. This study recommends a WBG technology maturation program to exploit these intrinsic advantages.

Packaging

Present packaging technology needs to be improved to support the high power density and high operating voltage of some WBG microwave components. Packaging and thermal management may be the performance limiters for WBG microwave devices and amplifiers. This study recommends that aggressive new approaches such as phase transition cooling be explored to insure adequate heat extraction for exploitation of the WBG dielectric strength advantages.

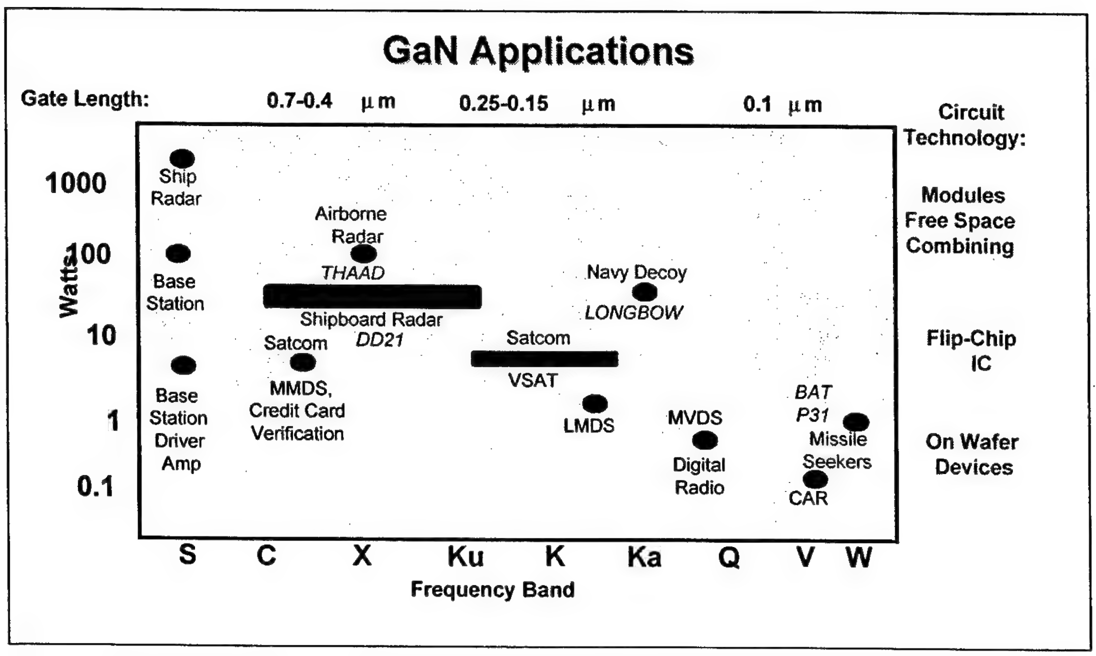

Fig. 8.1. Some commercial and Military Applications for GaN devices as a function of frequency.

Markets

There is a large commercial market for LED's and lasers based on GaN (>$400M in 1999 and projected to be $4.3 billion by 2009). In the near term, some aspects of this material infrastructure can be leveraged for DoD WBG RF technology. This study recognizes that adequate LED device yield may be achieved with present technology, but

that larger diameter, higher quality GaN material is required for large area (microwave) GaN MMIC devices.

There is an emerging market for high purity SiC material for gemstones. DoD can leverage this market for two inch-SiC substrate development since the high purity gemstone specifications are applicable to semi-insulating SiC substrates. This study qualifies this comment by noting that the gemstones are made from 6H SiC material whereas the optimum material for microwave power devices is 4H SiC. This study endorses further development of semi-insulating 4H SiC substrates.

Initial commercial markets for WBG RF technology will be narrow band, low frequency (1-6 GHz), and high linearity amplifiers for wireless base stations. These commercial applications will not directly address DoD system needs. There is a limited commercial market for pulsed RF power amplifiers.

Potential commercial markets for GaN HEMTs include Local Multipoint Distribution Systems (LMDS), Wireless Local Loops (WLL), collision avoidance radar, and satellite links.

The first WBG RF component (a 10 W SiC MESFET at 2 GHz) has been released by Cree Inc., as a commercial product. It has superior linearity compared to a Si LDMOS transistor, which enables less back-off, and thus, higher operating efficiency.

System Impact

WBG RF technology is being considered for use in the Navy Theater Wide (NTW) Ship Self Defense and Theater Ballistic Missile Defense (TBMD) radars. If the projected simultaneous achievement of high power, efficiency, and linearity from WBG microwave technology is realized, it should enable simultaneous multifunction electromagnetic systems. However, cost and thermal management considerations remain as challenges.

WBG RF technology is projected to provide power levels (40-100 W) comparable to those presently obtained from low power microwave power modules (MPMs), at frequencies below 30 GHz. Subsequent to the AGED STAR, WBG MMIC amplifiers have been demonstrated, as one of a kind laboratory results, that achieve pulse power outputs on the order of 25 watts in a size significantly smaller than that of an MPM. Such WBG RF technology may enable low cost, versatile, energy-saving, decoys and UAVs.

Active electrically scanned arrays (AESAs) are preferred to achieve low phase noise radar. WBG RF technology will enhance the performance of AESAs, especially when aperture size is limited. This will be made possible primarily by providing higher power per element and secondarily by (potentially) achieving improved linearity compared to that of alternative technologies.

The higher operating voltage of WBG amplifiers will improve the efficiency of power distribution and conversion in some solid-state systems over that of their silicon or GaAs cousins. For example, in an active electrically scanned array, higher voltage DC/DC converters will have increased efficiency. In another example, some levels of DC/DC conversion may be eliminated in the JSF where direct operation at 28 V is preferred. Subsequent to the AGED report, it has been learned that the next generation of satellites will use 56 volt power. GaN amplifiers can be expected to operate directly from this voltage source thereby substantially lowering power supply costs although some conditioning and load protection will be necessary

Based on demonstrated transistor noise performance, AlGaN HEMTs may enable robust, high dynamic range, receivers with a simplified design and reduced overall noise figure compared with present approaches. More robust GaN low noise amplifiers have been demonstrated, in the laboratory, to provide even larger dynamic range with commensurately lower limiter losses. This, in turn will lead to the lowest broadband receiver noise figures.

9. INVESTMENT STRATEGY

As a general rule, uncontested opportunities exist for VE S&T to fill high power millimeter wave applications and to fill other applications related to single function systems where cost is an issue. Applications using corporate-fed arrays and parabolic antennas will generally be addressed using VE technologies. Applications for which active aperture arrays are required generally make use of SS technology. Other VE opportunities exist on a case-by-case basis.

As a general rule uncontested opportunities exist for solid-state S&T to fill fusing applications and applications wherein simultaneous multifunctionality is required. To a lesser extent, all multifunctional applications and active aperture applications below 25 GHz, in the near term and below 50 GHz in the longer term, are expected to increasingly be met by solid-state technology. Solid-state technology is generally not the technology of choice for applications using corporate-fed arrays or parabolic antennas. Still other SS opportunities exist on a case-by-case basis.

A table of DoD historic and planned investment in solid-state and vacuum electronics at this time is provided in Table 10.1 below.

DoD RF Power Amplifier Funding							
		FY99	FY00	FY01	FY02	FY03	FY04
		$K	$K	$K	$K	$K	$K
Army	6.1 SS materials and devices	196	224	236	286	291	297
	6.2 SS materials and devices	1,710	2,130	1,773	2,094	2,385	1,916
	6.2 Vacuum Devices	350	450	450	450	450	450
	6.3 Vacuum Devices	50	250	300	100		
Navy	6.1 SS materials and devices	4,283	5,744	5,200	4,825	4,575	4,575
	6.2 SS materials and devices	690	3,985	4,149	3,304	3,004	3,004
	6.1 Vacuum Devices	794	815	830	746	418	400
	6.2 Vacuum Devices	11,000	10,090	7,500	4,505	4,505	4,505
Air Force	6.1 SS materials and devices	700	1,100	1,100	1,100	700	700
	6.2 SS materials and devices	930	550	3,500	2,700	3,300	2,700
	6.3/SBIR Materials	800	800	400	500	0	0
	6.2 Vacuum Devices	100	100	100	0	0	0
BMDO	6.3 SS	5,000	6,000	5,000	0	0	0
OSD	6.1 MURIs Vacuum	0	680	1920	1920	1920	1920
	6.1 MURI AlGaN High Power Amplifier Program	2,000	2,000	1,500	0	0	0
	6.1 MURI Ultra Low Noise Electronics Program			700	1,200	1,200	1,200

Table 9.1. Current DoD Funding Levels for RF Power Amplifier Technologies

9.1. *SOLID-STATE*

Solid-state power transmitter technologies can be defined and categorized by the semiconductor material used to make the active transistor. The dominant classes of materials are: Si (and SiGe); conventional compound semiconductors (GaAs and InP); and wide bandgap semiconductors (SiC and GaN). In addition, transmitter support technology encompassing packaging, interconnects, and thermal management must be considered. DoD investments must address technology areas that fall outside of commercial application needs. They must focus upon the DoD unique requirements of simultaneously achieving high power over large bandwidth with high efficiency and linearity. The investment strategy described below is grouped by underling material systems and the support technologies.

Silicon rf device technology is widely used in commercial application at 2 GHz and below. Silicon LDMOS and bipolar devices are being driven by commercial wireless applications, hence no DoD investment in these RF technologies is deemed appropriate or necessary.

- The commercial market for conventional compound semiconductors, namely GaAs and InP, is dominated by low power, high efficiency amplifiers for portable personnel communications (e. g. cellular phones). The required power level is generally <1 W for the portable applications. There is an additional commercial market for higher power base station amplifiers that is served by discrete large periphery transistors. These markets are presently at 2 GHz and below, but future generations are expected to move to 2 to 6 GHz spectrum. Future commercial markets at high frequency include local multipoint distribution systems (28 to 30 GHz), car collision avoidance radar (60 to 70 GHz), and satellite links (20 to 30 GHz). In general, the commercial applications are all low power (< 10 W) and narrow bandwidth (≤1%) ones. The military performance drivers are high power, high bandwidth, high linearity and efficiency, high reliability, and high frequency operation. These requirements drive DoD product selection to a monolithic amplifier solution. Maintaining high volume production of high yield, monolithic microwave integrated circuits (MMICs) is an ongoing challenge because of inherently low volume, non-continuous DoD procurements. S&T investments in GaAs and InP MMIC yield enhancement can address part of this problem, but a DoD-wide coordination effort for maintaining viable MMIC suppliers is also required. Significant cost reduction leverage is possible if the DoD can identify common transmitter requirements across multiple systems to foster an improved acquisition strategy. It appears that GaN devices and monolithic circuits, but not SiC ones, can be fabricated on existing GaAs MMIC production lines. This is one reason why a WBG technology maturation program will not be as expensive as the earlier GaAs MIMIC program was.
- Further areas requiring DoD investment in GaAs and InP technology are directed toward high frequency (>30 GHz) enhancements at the device, circuit, and sub-system level. With continuous encroachment by commercial users on the electromagnetic spectrum below 10 GHz, DoD systems may be forced to operate at high "mm-wave" (>30 GHz) frequencies. The extant S&T challenges are to further advance the device structures and circuit approaches so that manufacturable, high power, high efficiency, and high linearity components become readily available and affordable. A key area for investment is that of efforts toward maturation of metamorphic transistor structures. This would be accomplished by using a metamorphic buffer layer below the active device that serves to grade the lattice constant from that of the substrate to that of the active device. This technology has been demonstrated at several contractors including Raytheon and Sanders (now BAE) and offers advanced mm-wave devices on a lower cost (compared to InP) GaAs substrate that can be up to six inches in diameter. DoD investment in the continued development of this technology is deemed appropriate.

- Wide bandgap semiconductors (SiC and GaN) have been identified as enablers for high power solid-state transmitters for next generation radars, particularly for aperture size limited radars. They are also expected to offer significant system advantages for communications, electronic warfare systems, and multifunctional systems. While dramatic progress has been demonstrated with prototype SiC and GaN amplifiers over recent years, the material and amplifier-manufacturing infrastructure for these technologies is not sufficiently mature to support DoD acquisition programs. The need and scope of this investment has been identified by the solid-state working group under this study as well as by two other related activities. The first of these was an AGED Special Technical Area Review (STAR) on Wide Bandgap RF Technology, sponsored by DDR&E. The second was a Navy Radar Technology Roadmap study led by MIT Lincoln Laboratories and sponsored by the Navy's ASN/RDA. The recommended scope of this development was consistent across the three groups and consistent with the level of DoD investment directed toward maturation of Si and GaAs technology in the past (i. e., the DoD VHSIC program and DARPA's MIMIC and MAFET programs). The recommended program is presented in Table 10.2.

Wide Bandgap rf Technology Maturation Program		Y1	Y2	Y3	Y4	Y5	Y6	Total
Technical Trust								
Materials								
	Bulk 4H SI-SiC	5	5	5	5	5		25
	SiC epi	8	12	12	10	5		47
	GaN epi	7	10	12	8	5		42
rf Devices								
	New concepts and optimization		5	8	10	5		28
	Yield and Process Optimization	4	4	8	12	12	10	50
	Failure Analysis and Reliability		2	4	4	2		12
	Packaging and Thermal Management	4	4	8	6	2		24
Circuits								
	Design Tools		4	8	6	4		22
	Power Combining		4	6	4			14
	Passive Components		2	2	2			6
Total = $M		28	52	73	67	40	10	270

Table 9.2. Recommended investment for Wide Bandgap RF Power Technology

Related areas of S&T investment for both conventional compound semiconductors and the wide bandgap semiconductors include packaging, thermal management, and interconnects. Packaging and thermal management are strongly interrelated, particularly in the case of high power density amplifiers. The investment in this specific area is included in the wide bandgap RF technology maturation plan shown in Table 10.2 and its cost is estimated to be $24M, over 5 years. Packaging cost and

ruggedness (e. g. can the package withstand high temperature and/or high voltages) are also areas for development. This work could most likely be addressed in part under the high power density packaging effort presented above.

The S&T investment required in the area of interconnects relates to the development of three dimensional circuit architectures or conformal arrays. These will add functionality within smaller circuit sizes. An example of such a circuit is a flexible conformal transmitter array for UAV's. The approach under consideration would integrate dissimilar materials and devices or circuits to enable optimum system performance. Advances are needed in device, circuit, and system level modeling of such heterogeneously integrated technologies as well as in the approaches to reliably combine dissimilar technologies. The level of funding for this work is shown in Table 10.3.

Technical Thrust	Y1	Y2	Y3	Y4	Y5
Flexible interconnects	$3M	$3M	$3M	$3M	$3M

Table 9.3. Recommended funding for flexible interconnects

As discussed above investments must be made to bring GaAs to a higher level of maturity in order to lower acquisition costs. After achieving this status, it must be maintained to assure availability of GaAs devices and MMICs for DoD use. InP must be developed to full maturity, including realization of high yield, large wafer SPC controlled fabrication lines. Table 10.4 illustrates the recommended program for GaAs and InP maturation activities.

Technical Thrust	Y1	Y2	Y3	Y4	Y5
GaAs Productivity	$5M	$5M	$5M	$5M	$5M
InP Development	$5M	$5M	$5M	$5M	$5M

Table 9.4. Recommended funding for GaAs and InP maturation program.

Summary of Solid-state Funding and Program Recommendations

1. RECOMMENDATION: **Silicon and silicon-germanium RF technology requires no DoD investment.**
2. RECOMMENDATION: **GaAs Producablity and InP technology should be supported at a level $5M per year per thrust.**
3. RECOMMENDATION: **A wide bandgap rf technology maturation program should be initiated at a level of roughly $250M over 6 years.**
4. RECOMMENDATION: **Packaging and thermal management of high power density amplifiers should be addressed under the wide bandgap program.**
5. RECOMMENDATION: **Interconnects and advance flexible array concepts should be supported at a level of $3M/yr over 5 years.**

Roadmaps

A concerted effort by the Reliance Tri-Service TPED has resulted in the RF Solid-state Power and Electronic Materials roadmaps that are presented in the Appendix A of this report. A recently completed Navy S&T Radar Technology Roadmap is not included, but excerpts from it are quoted throughout and its conclusions regarding power amplifier requirements are used in this study. System insertion opportunities as well as recommended investment levels to achieve those system insertions are represented.

9.2. *VACUUM ELECTRONICS*

9.2.1. FUNDING

FINDING: By FY88, VE technology funding levels had fallen to $12.6 million (FY01 constant dollars). (See Figure 10.1.) This level of support was considered highly inadequate. To remedy this critical situation, OUSD(A)/DDRE established and funded the Tri-Service/DARPA Vacuum Electronics Initiative, which has had outstanding successes over the last ten years.

The current FY01 vacuum electronics funding level is $7.70 million (FY01 constant dollars), i.e., it is at 61% of the funding level deemed sub-critical in FY88. Defense needs have increased since FY 88 and affordability has become a key issue; however, current funding is well below the critical threshold to sustain VE.

The VE funding levels shown represent all known sources. Since 1988, DARPA funding has been zeroed and Air Force and Army funding have diminished to negligible amounts. On the other hand, WBG semiconductor technology is accruing funds from a variety of Service and DARPA sources. The programs are at the pre-MIMIC program phase of development, with at least ten years to manufacturing maturity and economic viability.

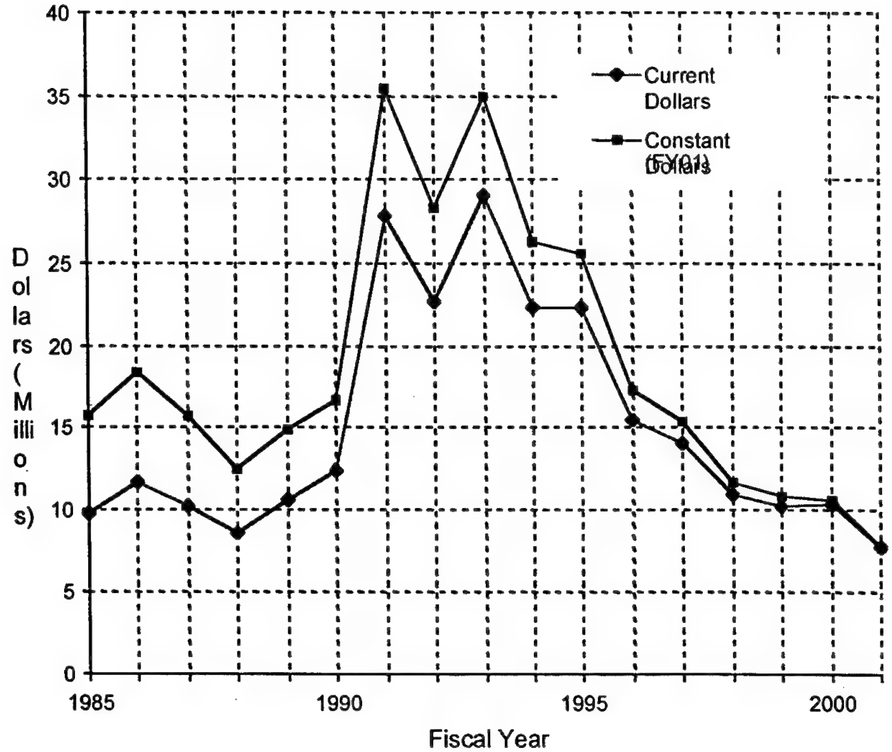

Fig. 9.1. Vacuum Electronics Applied Research Funding (FY85 – FY01)

RECOMMENDATION: Restore vacuum electronics Navy 6.2 funding to FY98 levels of $12 million (FY01 constant dollars) per year for five years.

9.2.2. RELATIVE CAPABILITY

FINDING: The capability of vacuum electronics technology to meet many and varied defense electromagnetic warfare requirements continues. There is no discernible reason why vacuum electronics advantages will not persist in single function system applications and to a lesser extent will continue to offer comparative advantages in certain active aperture systems since its strength is based in the physics of the transport medium. Vacuum electronics also displays performance superiority for:

- Device power production at millimeter-wave frequencies,
- Efficiency measured at the device level, and
- Power – bandwidth capability at both microwave and millimeter-wave frequencies.

RECOMMENDATION: Reduce the risk to future DoD electromagnetic warfare systems by leveraging the technical strengths of vacuum electronics for RF transmitters by supporting the technology activity at funding levels commensurate with its relative strength until the as-yet unproved wide bandgap semiconductor technology meets system performance needs and affordability goals.

9.2.3. System Insertions

FINDING: The vacuum electronic attributes of high efficiency, power-bandwidth capability, and high-frequency performance dictate its presence in legacy system upgrades (see below) and selected new systems, for the long-term. Specific application opportunities include:

- Electronic attack systems implemented in space-, weight-, and prime-power-constrained systems (aircraft ECM, off-board countermeasures, UAVs, mobile ground systems);
- High-data rate communication systems requiring microwave and millimeter-wave frequency support of complex modulation schemes (in UAVs, space borne, and mobile uplink systems);
- Radar systems implemented in space-, weight-, and prime-power-constrained systems (missile seekers, & mobile ground systems,); most corporate-fed antennas, and
- Fixed high-power high-frequency radar systems for range instrumentation (Pacific Missile Range Facility, Kwajalein Missile Range) and space object identification (HUSIR).

RECOMMENDATION: In addition to Applied Research funding support, funding lines should be established to transition advances in technology into Service systems.

FINDING: Major Service legacy systems are expected to be in inventory beyond the year 2025. The cost of modulator conversion, software development to accommodate different waveforms and threat data, and existing inventory of system sub-components dictate against conversion of most systems to a new technology. The attributes of vacuum electronics mentioned above coupled to these acquisition and life-cycle upgrade costs argue for the viability of a vacuum electronics technology base to support performance upgrades with cost parameters. Specific systems include:

- AEGIS SPY-1 upgrade requires existing power levels but with broader bandwidth, higher duty, and lower noise. These requirements can likely be satisfied by multiple-beam klystron (MBK) technology but this upgrade is not currently on the Navy Radar Technology Roadmap.

- AN/TPQ-47 FIREFINDER mobile radar, which recently rejected SiC technology as a result of technology immaturity, will require future high-performance TWT technology, and
- Support jamming and self-protect airborne electronic attack system upgrades will migrate toward broadband MPM and MMPM systems, thereby reducing logistics costs while upgrading performance

RECOMMENDATION: Support the vacuum electronics technology base throughout major system life to take advantage of upgraded performance attainable through the use of physics-based modeling of performance and manufacturability, as well as better ceramics, magnetics, and emitters.

9.2.4. BASIC RESEARCH

FINDING: Since FY88, Basic Research funding has declined from $7.4 million (FY01 constant dollars) to $2.3 million, a decline that has throttled the influx of scientific talent and innovative ideas. Currently, the major component of the vacuum electronics 6.1 program is the MURI, which is based on a three-year funding cycle with an option for two additional years.

RECOMMENDATION: Restore Basic Research 6.1 funding to at least $5M per year.

9.2.5. APPLIED RESEARCH

FINDING: The core of the vacuum electronics program has been conducted at the Naval Research Laboratory, with funding from the Office of Naval Research. The successes of the program over the last decade have been impressive. Due in part to the integrated technical program, focused funding, Tri-Service management, and the strength of the research team, the following successes are notable:

- The Microwave Power Module (MPM) was innovated by NRL and is now found in electronic attack, communications, and radar systems of all Services and may be viable for use by the commercial sector;
- The gyroklystron has achieved record-setting power and bandwidth at W-band and has been integrated into the WARLOC radar in collaboration with the NRL Radar Division. This high-peak-power device is being considered for critical space object identification and Navy missile range applications; and
- Modeling and simulation of traveling-wave tubes (TWTs) has achieved a record of first-pass design success, and the physics-based numerical codes are being transitioned to industry, where they are used for the development of both defense and commercial products.

RECOMMENDATION: Support continuation of the current effort by maintaining Navy 6.2 funding level at $12 million per year to support the program as shown in Table 9.5 below with Tri-Service Coordination.

9.2.6. ADVANCED DEVELOPMENT

FINDING: Minimal 6.3 funds (less than $0.2 million in FY01) are available to support transition of the advances of vacuum electronics Applied Research Program to system applications. Several important programs have suffered from the lack of Advanced Development funds:

- Technology developed under the millimeter-wave power module (MMPM) program is not yet tailored to SMART-T requirements at MILSTAR frequencies.
- Ion noise reduction has not yet been completely implemented in the Mk-99 AEGIS Illuminator.
- Fixed high-power high-frequency radar systems for range instrumentation (Pacific Missile Range Facility, Kwajalein Missile Range) and space object identification (HUSIR) require transition funding.

RECOMMENDATION: Expedite technology transition by identifying partnerships with Program Offices to co-fund specific Applied Research activities that have short-term application in military systems in accord with the program shown in Table 10.6 below. Vacuum Electronics: Advanced Development Budget

Thrust	Participants	Funding ($K) FY-02	FY-03	FY-04	FY 05	FY 06
Multiple-Beam Amplifiers	Ind. / Univ. / Lab	2,000	2,100	2,500	2,800	2,500
Linear Wideband Amps	Ind. / Univ. / Lab	2,265	2,100	2,200	2,300	2,200
Millimeter-Wave Amps	Ind. / Univ. / Lab	500	800	700	500	1,000
Hi-P. MMW Gyro-Amps	Ind. / Univ. / Lab	2,100	2,000	1,500	1,300	1,200
Modeling and Simulation	Ind. / Univ. / Lab	3,100	3,000	3,100	3,100	3,100
Sub-Component Tech	Ind. / Univ. / Lab	2,035	2,000	2,000	2,000	2,000
Funding Total		**12,000**	**12,000**	**12,000**	**12,000**	**12,000**
Industry - Ind., University - Univ., and Government Laboratory - Lab.						

Table 9.5. Proposed Applied Research Funding for Vacuum Electronics Technologies.

9.2.7. ADVANCED DEVELOPMENT BUDGET

Thrust	Participants	Funding ($K) FY-02	FY-03	FY-04	FY 05	FY 06
MPM & MMPM	Ind. / Univ. / Lab	4,000	4,000	3,500	3,300	3,300
Millimeter-Wave Amps	Ind. / Univ. / Lab	2,700	2,700	2,500	2,350	1,450
Test Range Gyro-Amps	Ind. / Univ. / Lab	2,000	2,000	1,500	1,000	1,000
Multiple Beam Klystrons	Ind. / Univ. / Lab			1,000	2,050	2,950
Industrial Infrastructure	Ind. / Univ. / Lab	1,300	1,300	1,500	1,300	1,300
Funding Total		**10,000**	**10,000**	**10,000**	**10,000**	**10,000**
Industry - Ind., University - Univ., and Government Laboratory - Lab.						

Table 9.6. Proposed Advanced Development funding for Vacuum Electronics Technologies.

10. SUMMARY

Over the course of two years, an ad-hoc committee of senior S&T managers from the Army, Navy, and Air Force met to formulate an S&T investment strategy which provided an appropriate S&T funding balance between SS technology development and VE technology development in the area of RF power components for electromagnetic systems. The committee sponsored two workshops as follows:

A requirements workshop was held in July, 2000 and

An S&T Opportunities workshop was held in October, 2000.

The Committee concludes, in this final report to senior S&T policy makers within the Services, that the DoD's S&T investment in RF component technology is insufficient to meet emerging threats and has outlined a set of programmatic and funding recommendations to redress these deficiencies.

11. DISCLAIMER

This document does not represent the official policy or position of the US Army, ARL, the US Navy, ONR, NRL, the US Air Force, or AFRL.

12. ACKNOWLEDGEMENTS

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13. AD HOC TRI-SERVICE COMMITTEE MEMBERS

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14. APPENDICES

APPENDIX A: TECHNOLOGY ROADMAPS

APPENDIX B: SYSTEMS THAT WILL USE SS AND VE POWER AMPLIFIERS

APPENDIX C: NON-CONCURRING COMMENTS AND ISSUES

APPENDIX A: TECHNOLOGY ROADMAPS

TRI-SERVICE RF POWER TECHNOLOGY ROADMAPS

Investment Area: Solid State RF Power

Joint Warfighter Capability Objectives: Information Superiority, Precision Force

Technology Challenge: More Capable Solid State RF Power Amplifiers

Technology Transition (FY98 – FY08)

- UAV/UCAV Com Link — Predator/Golbal Hawk Tech Insertion
- DD21 (Integrated Sensor) — Technology Demos, 2-20 GHz Components; CDR - AMRFS Tech Freeze
- High Power S-Band Radar (ATMD) — Technology Demo, 300 Watt S Band; Tech Freeze; EMD
- Millimeter Wave Seekers/Support Sensors — Technology Demos, BAT, TERM, Hell Fire, Hammerhead; GBU-15 Tech Freeze
- EW/Jammers Arrays (Joint Service Support) — Wideband Array Technology Demo; JSSJ Tech Freeze; Top Attack CM

Technology Tasks — Investment Plan ($K)

Technology Tasks		FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08
Silicon Carbide / *Silicon Carbide 2* / L to C-band radar, EW, comms	F	2752	2507	547	1470	290						
							10000	22000	25500	19000	8000	4000
Gallium Nitride / *Gallium Nitride 2* / C-band and above, RADAR, EW, coms	F	500	2653	8672	10080	3320	1030	500	500			
							8000	19000	26500	23000	12000	4000
Indium Phosphide / *Indium Phosphide 2* / > 30 GHz, coms, seekers	F	0	793	2523	3291	5542	5312					
				1000	1500	3500	3500	3500	3000			
Gallium Arsenide / *Gallium Arsenide 2* / X-band to Ka-band comms	F	502	1081	1412	1683	1408	1874					
				500	1000	2000	2000	1000	1000			
Silicon Germanium / *Silicon Germanium 2* / <S-band comms		300	300	300								
Total Planned Funds	F	[illegible]54	7334	13454	16524	10560	8216	500	500	0	0	0
				1500	2500	5500	23500	45500	56000	42000	20000	8000

SiC Version 2 — Investment Plan ($K)

Device Type	Performer	Maturity	*Return* Organization PE/Proj - UF	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06
Devices Technology												
SIT												
1-5 GHz, inverted SIT	Northrop-Grumman	R	62234N				270					
MESFET												
2-8GHz BW, 30W MESFET		R	DARPA (MAFET)	1700	1650							
1-5 GHz, power FET	Cree	P	62234N			227	500	290				
10 GHz, 40 Watts, >30% eff	Cree	R	6XXXXE	752	655							
									5500	12000	11000	6500
BJT/HBT												
SiC Bipolar Hi-linearity Transistor	Astralux/Extreme Devices	R	OSD SBIR			170	700					
3 GHz, 300 Watts long-pulsed, >35% eff	Northrop-Grumman	R	62204F	300	202	150						
IMPATTs/NDR's												
10, 35 GHz SiC	TDI											
Supporting Activities												
Reliability										1500	1500	1500
Modeling & Simulation									1000	2000	2000	2000
Packaging (see packaging roadmap), Thermal Issues									1500	2500	4000	4000
Module Integration									2000	4000	7000	5000
Total Planned Funds			Funded (F)	2752	2507	547	1470	290	0	0	0	0
									10000	22000	25500	19000

GaN Version 2			*Return*	Investment Plan ($K)								
Device Type	**Performer**	Maturity	**Organization PE/Proj - UF**	**FY98**	**FY99**	**FY00**	**FY01**	**FY02**	**FY03**	**FY04**	**FY05**	**FY06**
Devices Technology												
SIT												
MESFET												
HEMT									3500	9000	12000	10500
FET Technology, 4-20 GHz 50% PAE devices	Cree	R	62234N	500	1400	1950	1950	1100				
1-18GHz Driver	Northrop-Grumman	R	62234N			327						
4-20GHz Power Amplifier	Cree	P	62234N			208	500	290				
Recessed Gate Technology	NRL	R	62234N				130	130	130			
1-18GHz Driver	UCSB	R	62234N			225	225					
Wideband Power Amplifier	Cree Light.	R	62234N			287						
GaN/InGaN HEMT	NRL	R	62234N				450	500	500	500	500	
W-band Power>400 mw, Ka Power 5 - 10 W	Cree	R	62234N				400	400	400			
10 GHz, 40W, 50% eff	Malibu Research Lab	R	BMDO		500	750	750	750				
X-band, 8-12Ghz, 20W	Multiple: Cree, TRW, UCLA, Raytheon	R R	BMDO/TOS			4500	5200					
10 GHz, 25 Watts, 50% eff	Cree		DUST/62204F		528	100	250	150				
BJT/HBT												
HBT Power Amplifier	Cornell	R	62234N			100						
AlGaN HBT	UCSB	R	62234N		225	225	225					
IMPATT/NDR's												
Supporting Activities												
Reliabiltiy										1500	1500	1500
Modeling & Simulation									1000	2000	2000	2000
Packaging (see packaging roadmap)									1500	2500	4000	4000
Module Integration									2000	4000	7000	5000
Total Planned Funds			**Funded (F)**	500	2653	8672	10080	3320	1030	500	500	0
									[illegible]	19000	26500	23000

Millimeter Wave Amplifiers			***Return***	**Investment Plan ($K)**								
Technical Sub-Task	Performer	Maturity	**Organization PE/Proj - UF**	**FY98**	**FY99**	**FY00**	**FY01**	**FY02**	**FY03**	**FY04**	**FY05**	**FY06**
MHEMTS & InP DHBT MMICs		A						500	[illegible]	500	500	
Deep sub-μ InP/InGaAs/InP	**UCSB**	**R**	62234N				144	144	[illegible]			
InP/InGa/As HBT on GaAs	**UCSB**	**R**	62234N				140	140	[illegible]			
Technology												
20-40 GHz, 10W, 45% efficiency						350	400	400				
Millimeter Power Technology *(material=?)*												
W-band Power>400 mw, Ka Power 5 - 10 W	**IH**	**R**	62705A/AH94		793	1173	1107	1358	1528			
Ka/W band 3D Power Combiner Technology		**P**	S&T			1000	1500	1500	1500	1600	1000	
Linear Amplifiers for Satcom			S&T					1500	1500	1600	1500	
Total Planned Funds			**Funded (F)**	0	793	2523	3291	5542	5312	3500	3000	0
						1000	1500	3500	3500	3500	3000	

GaAs Sheet, PHEMT, Tl-doped GaAs

GaAs Sheet, TlGaAs PHEMT Demo

Ref: Materials Roadmap

TERM

Future Scout EMD

GBU-15

Future Combat Vehicle

BAT P3I

Comanche LongBow EMD, Apache LongBow Upgrades, SEPS

Millimeter Wave Amplifiers			*Return*	Investment Plan ($K)								
Technical Sub-Task	Performer	Maturity	Organization PE/Proj - UF	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06
Dual Band GaAs Amplifiers												
X/Ku, 80W MMIC Combiner	Raytheon	R	62204F				150	150	500			
		P					500	1000	1000			
Custom Semiconductors/Devices Processes												
Explore TIGaAs, GaInAsN u>10,000cm2/v-s	IH	R	62705A/AH94		468	500						
TIGaAs Producibility Demonstration		P	P				500	500	500	500	500	
High Speed Electronic Devices												
Robust PHEMT process, Tl-doped GaAs	IH	R	62705A/AH94	502	613	912	908	1133	1249			
TIGaAs PHEMT Producibility Demonstration		P	A/AF/N - UF			500	500	500	500	500	500	
Millimeter Power Technology *(material=?)*												
Multi-function	NWC	P	62234N				125	125	126			
W-band Power>400 mw, Ka Power 5 - 10 W	*IH*	*R*	*62705A/AH94*		793	1173	1107	1359	1528			
Ka/W band 3D Power Combiner Technology		*P*	*S&T*			1000	1000	1500	1500	1500	1000	
Linear Amplifiers for Satcom			*S&T*					1500	1500	1500	1000	
Total Planned Funds			Funded (F)	502	1081	1412	1683	1408	1874	0	0	0
						500	1000	2000	2000	1000	1000	

Module Prototype

Predator

APS

Attributed to InP Sheet, not incl. with this funding.

TERM

Future Scout EMD

GBU-15

Ref: Materials Roadmap

Future Combat Vehicle

BAT P3I

Comanche LongBow EMD, Apache LongBow Upgrades, SEPS

Millimeter Wave Amplifiers			*Return*	Investment Plan ($K)							
Technical Sub-Task	Performer	Maturity	Organization PE/Proj - UF	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05
S-Band SiGe Transistor											
3.0 GHz, 300 Watts, short pulse	Northrop-Grumman	R	602234N	300	300	300					
Total Planned Funds			Funded (F)	300	300	300	0	0	0	0	0

SiC Sheet, SiC MESFET Prod. Demo

APPENDIX B: SYSTEMS THAT WILL USE SS AND VE POWER AMPLIFIERS

RF TRANSMITTER SYSTEMS / DISCRIMINATORS / GAPS

Radar		*Communications*		*Electronic Warfare*		*Multifunction*		*Weapons Control*	
AN/TPQ-47	D	SMART-T	D	ALE-50	U	AMRFS	P	AMMRAM	U
				ALE-55	U				
		FCS	P	ALQ-131	U			PAC-3	D
AN/TPQ-75	U	Ultra-Comm	P	ALQ-184	U	MFRF	D	MRK-99	D
SPY-1(SS)	D	UAV-Comm	D	ALQ-172	U			APG-78(Longbow)	U
SPY-3	D	SINCGARS	U	AOA	P	DD-21	P	A-A	P
FOPEN	D	NearTermDigitalRadio	D	ALQ-211	U	SPY-3	D		
		Digital Comm	D	ALQ-135	U			BAT	D
UAV(TESAR)	D	GlobBroadcastSys.	U	ALQ-161	U			SADARM	U
Gnd Veh	D	JTRS	D					MM Hellfire	D
GLOBAL HAWK	D	CEC	D					THAAD	D
Periscope Detection Radar	P	SEA Comm	D	SIRFC	D	UAV-MULTI	P	Commanche(FCR)	U
JSF	D	Future SpaceBsdComm	P	SLQ-32	D				
MRRS	D			EA6-B	U			A-G	P
SBR	P	Future Gnd Station	P	AIEWS	D	FCS	P		
MEADS	D							NMD	P
TRAM	P							TBMD	P
GBR	D			UAV-JAM	P	THAAD	D	NTW	P
Air ID	D			PROPHET	D			Cruise Missile	D
HUSIR	P			UAV-SEAD	P			Future Missile	P
NTW	P			Adv. NULKA	D			Seeker(Dual Mode)	D
SENSORCRAFT	P			MALD	P			Adv. SAR	P
TACS Radar	D							Radiometer	P
Penetrator	P							Fuze Xmtr	P
LEO-ESA	P								
MEO-LL	P								
Gnd.Penetration Rad.	D								

U=Upgrade, D=Develpoment, P=Proposed

Sheet 1